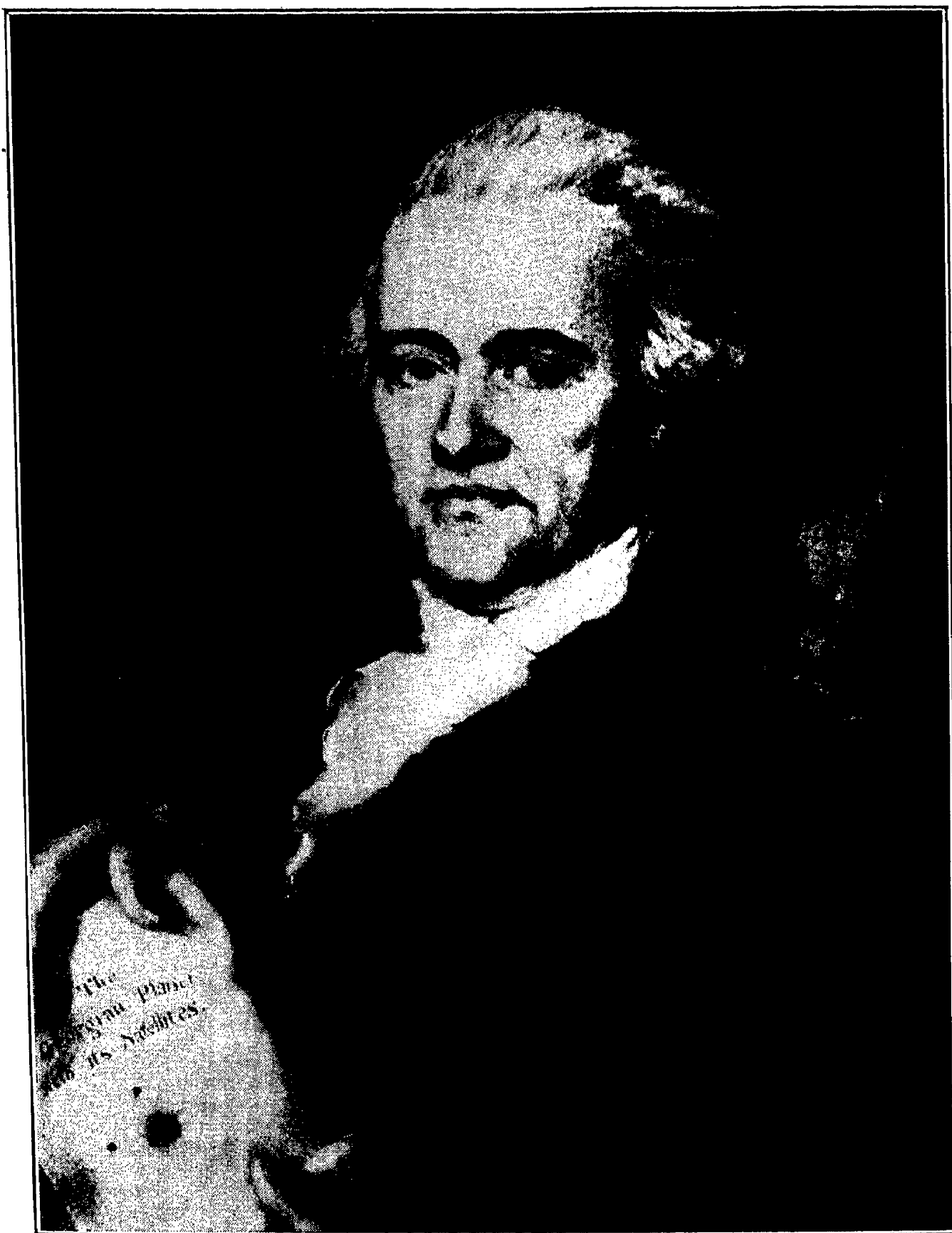


PHOTOGRAPHY BY INFRARED



Sir William Herschel, discoverer of the infrared.

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PHOTOGRAPHY BY INFRARED

ITS PRINCIPLES *and* APPLICATIONS

By

WALTER CLARK

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Kodak Research Laboratories

SECOND EDITION

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SECOND EDITION
Second Printing, April, 1947

PRINTED IN THE UNITED STATES OF AMERICA

Dedicated to

DR. C. E. K. MEES, F.R.S.

“ . . . the eye of the camera would see plainly where the human eye would find nothing but darkness. Alas! that this speculation is somewhat too refined to be introduced with effect into a modern novel or romance; for what a dénouement we should have, if we could suppose the secrets of the darkened chamber to be revealed by the testimony of the imprinted paper.”

WILLIAM HENRY FOX TALBOT,
“The Pencil of Nature,” 1844.

Preface to the Second Edition

The printing plates for the first edition were destroyed in the air raids on London. It was not possible to remake the book during the war, and from some points of view this was an advantage for the new edition, because it gave time to acquire copies of the wartime literature published on the European continent.

Quite a lot of infrared photography has been done in recent years, and many new applications have resulted. Much more is now understood about its usefulness and limitations for the general photographer and the scientific and technical people. Great progress has been made with infrared films, which are now as fast and as stable as commonly used panchromatic films. The book has been thoroughly revised to inform the reader of these latest developments, and the extensive bibliographies have been brought up to date.

Among the changes made in the second edition are: a new chapter (XIII) on camouflage detection by infrared, and a new section on forest survey from the air; thorough revision of the sections on photography in the dark, measurement of temperature by infrared, the infrared focus of lenses, properties of paints and pigments with special reference to the examination of paintings, criminology, the properties of foliage in the infrared, medical photography and photomicrography, aerial photography, and modern sensitometry and systems of speed designation.

WALTER CLARK

Rochester, N. Y.

1946

Preface to the First Edition

The invisible part of the spectrum called the infrared has been known since the beginning of last century, and portions of it have been photographed for more than fifty years. Infrared photography is thus by no means a new subject. In 1931, however, discoveries were made which enabled it to be practiced by the general public with the ease of ordinary photography. At the present time the public is, consciously or unconsciously, very much concerned with photography. Not only does it use it as a hobby, but it relies upon it to an increasing extent for its knowledge of the world at large and for entertainment, and it has come to accept it as one of the most important instruments by which the scientist has been enabled to make the discoveries which have played the outstanding part in determining modern progress. Study of the infrared is now a very important part of the whole photographic field, and the interest in it is reflected by innumerable references in the popular, photographic, scientific and technical press. This literature is very widespread, and the time would now seem ripe for its material to be brought together within the confines of one volume.

The closest approach to perfection in the practice of an art or a science can be obtained most easily and with the greatest prospect of success through a knowledge of the principles basic to the practice. In this book, therefore, the attempt has been made to deal not only with what is known of infrared photography, but also with the underlying principles. It is hoped that as a result of this the photographer will be able to apply the subject intelligently to the varied problems which present themselves, and that those who are interested in utilizing its results will be aided in the appreciation of its possibilities and the interpretation of its findings.

The book is intended for the guidance of the practical infrared photographer, whether he is concerned with the commercial or artistic aspects of its subject or its applications in the scientific

and technical fields. It is assumed that the reader will have some acquaintance with the practice of ordinary photography. No scientific knowledge is necessary for the understanding of the practical part of the book, and, where the underlying principles are dealt with, the attempt has been made to discuss them in as simple a manner as possible.

At the end of each chapter a list of references is given to all the useful published papers which were known to me. With the exception of about a dozen articles, which were available only in abstract form, I have read all the original texts.

I am much indebted to Dr. C. E. K. Mees, director of research and development of the Eastman Kodak Company, who is responsible for my interest in the subject, and to my friend, Dr. C. W. Fox, who read the entire manuscript and made many valuable suggestions. I am deeply grateful to all those who have assisted me by reading and criticizing those portions of the text treating of subjects in which they are expert, and in particular to Dr. L. G. S. Brooker, Dr. B. H. Carroll, Mr. J. I. Crabtree, Dr. L. A. Jones, Mr. R. P. Loveland, Mr. R. C. Edwards, Dr. L. C. Martin, Mr. G. E. Matthews, Mr. J. W. McFarlane, Mr. A. Murray, Mr. E. E. Richardson, Mr. M. E. Russell, Mr. A. L. Schoen, Dr. J. Sterner and Mr. K. S. Weaver. Acknowledgment is made in the text and lists of references to those whose published work provided the basis for much of the material for the book, and to those who so kindly granted permission for their data and illustrations to be reproduced. The I. G. Farbenindustrie A.-G. (Abteilung Agfa), the Agfa Ansco Corporation, the Eastman Kodak Company, and Messrs. Ilford Ltd. kindly provided information concerning their products.

WALTER CLARK

Rochester, N. Y.

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Chapter I

THE SUBJECT

Through the dawn of day and the fall of night and the passing of the seasons, primitive man first became acquainted with the association between light and heat. It was brought home still more dramatically through his own artifices when he learned to make fire by rubbing together two pieces of wood, for in this manner he was provided with a luminous flame by which to see and a means by which to cook his food and warm himself. In all stages of civilization man has recognized the benefits of light and heat and the fact that the means employed to produce the one generally gives rise to the other. In the fire of Aristotle they were combined as one of the basic elements of the physical world. Even the burning glass was known to the ancients, for we find that they used glass globes filled with water to concentrate the rays of the sun and so produce fire. From those early days up to the present time, as science became more and more grounded on a firmer basis, man's knowledge of the behavior and nature of these associated principles of light and heat grew. He now knows them to be closely related phenomena in the realm of the concept which the physicist calls radiation. From the early observations on the behavior of light and heat this science of radiation has grown, and from it most of our knowledge of the nature of matter has been derived.

The subject of this book is the photography of those radiations which are known as the "infrared." It will be shown a little later that these are identical with the rays of heat, and they are, therefore, associated with light. In fact, in order to obtain a clear understanding of the subject, we must first of all study some of the characteristics of the light which we can see, and then extend our interest to its close relative, the infrared. This is important, not only for an insight into the nature of the infrared, but also because most photographs are made by visible light,

and a knowledge of the practice and principles of ordinary photography is essential to successful photography by infrared.

For our starting point we must go back as far as the seventeenth century. From a hole in a shutter in a darkened room, Sir Isaac Newton passed a beam of sunlight through a prism of glass and found that it was broadened out into a band which exhibited the colors of the rainbow. He thus showed that white light had a compound structure. He confirmed this in another experiment, by which he showed that the colors so obtained could also be recombined to form white light.

Newton's experiment is shown diagrammatically in Figure 1. The broad colored band is known as the "spectrum." The colors range from violet at one end to red at the other and pass through blue, green, yellow, and orange. The rays are bent to different degrees on emerging from the prism, the red end of the spectrum being formed by those which are least bent and the violet end by those which are deviated the most. The ends of the spectrum appear duller than the middle, which attains its greatest brightness in the yellow-green.

The curiosity of the natural scientist led him to wonder about the nature of light and to seek an explanation for its striking behavior. Newton himself thought of it as a stream of minute corpuscles in flight, rather like the bullets from a miniature machine gun. In Newton's time, however, there was another theory proposed by Huygens which also assumed the existence of corpuscles, but regarded them as packed closely together, in such a manner that light was propagated by the transmission of shocks from corpuscle to corpuscle. This view of Huygens was the immediate forerunner of later theories, developed by Young and Fresnel, according to which light was considered as traveling in waves. It was believed to move through space after the manner in which ripples travel across the surface of water. These waves were shown later to be electromagnetic in character, and, in order to provide some medium through which they could travel, the idea of the so-called "ether" was developed. In recent years observations have been made which cannot be explained on the basis of the wave theory, and they seem to require the application of a corpuscular theory like that of Newton. Physicists at the

present time have found a way of reconciling these two opposing ideas.

For our purpose, we can regard light as a form of energy which travels through a hypothetical medium, known as the ether, in the form of waves of electromagnetic origin. Waves, whether they are on the sea, in the ether, or in any other medium, have a number of characteristics which can be ascertained by simple observation. For instance, they travel through the medium; they may, therefore, be said to have *velocity*. They have crests, or

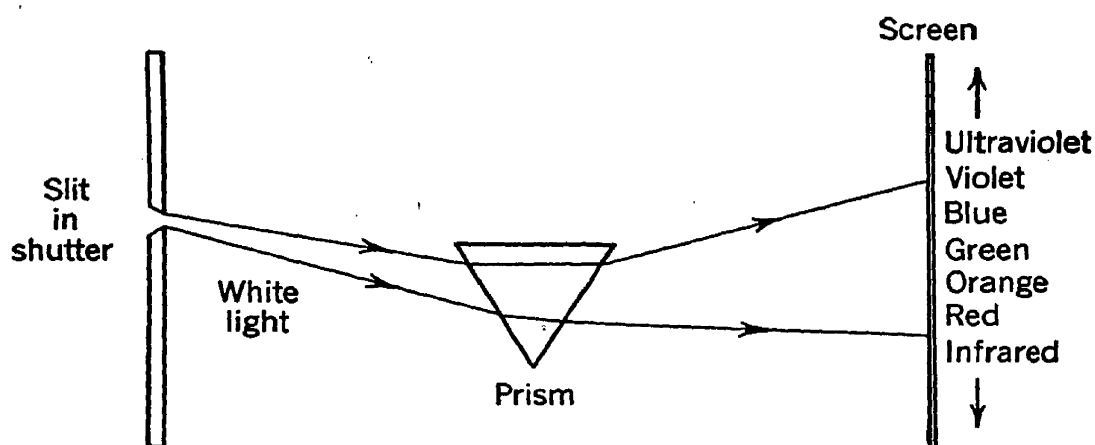


FIG. 1. Formation of the spectrum by the dispersion of white light.

troughs, which are separated by definite distances; the distance between two crests or two troughs may be called the *wavelength*. In a particular time, say, one second, a number of waves pass a particular spot; they thus may be said to have *frequency*, which is the number of vibrations of the wave in each second.

Clearly, these values of velocity, wavelength, and frequency are related to each other in a simple manner. If different waves travel at the same velocity, the wavelength will be shorter if the frequency is higher, and vice versa. This may be expressed by the simple equation

$$V = n\lambda$$

in which V is the velocity, λ the wavelength, and n the frequency. The velocity of light appears to be constant—about 186,000 miles per second. The two things which can be varied are the wavelength and frequency. It is customary in photography to refer to the wavelength of light, rather than to its frequency, and therefore the so-called “scale of wavelengths” is used in this book.

Most people are familiar with the concept of wavelength from their association with radio receiving sets. They know that the radio waves differ in wavelength, some being long while others are short. One station may broadcast using waves which are over 1,000 meters long, whereas another may use a wavelength of some 20 meters. It is known that the waves of light are identical in their nature with those of radio; they differ only in their wavelength, the property which determines their differing behavior. The waves of light which we can see are very much shorter than those of radio, which are invisible and require properly tuned receiving sets to detect them. Light waves are, in fact, so short that it would be very cumbersome to designate their wavelengths by the units commonly employed in measurement. Special units of wavelength therefore are employed, the commonest of which is the angstrom, which is one ten millionth part of a millimeter. Other larger units are the micron and the millimicron, which are used by scientists for special purposes. The relationships among the three units are shown in Table I.

TABLE I

UNITS OF WAVELENGTH

<i>Name</i>	<i>Symbol</i>	<i>Value</i>
Micron	μ	$1 \mu = 10^{-3} \text{ mm} = 10^{-6} \text{ m} = 10,000 \text{ A}$
Millimicron	$\text{m}\mu$	$1 \text{ m}\mu = 10^{-6} \text{ mm} = 10^{-9} \text{ m} = 10 \text{ A}$
Ångstrom unit	A	$1 \text{ A} = 10^{-7} \text{ mm} = 10^{-10} \text{ m}$

In the spectrum obtained by passing white light through a prism, there is a progressive increase of wavelength from the violet at one end to the deep red at the other. The limits are at about 3,900 A for the violet and 7,600 A for the deep red. We can see nothing at wavelengths shorter and longer than these. The question immediately arises: Does the fact that we cannot see anything beyond these limits exclude the possibility of there being invisible wavelengths shorter than the violet and longer than the red? Scientists were interested in the answer to this question from the time that Newton discovered the spectrum. We have already seen that light is usually associated with heat. What relation does this heat bear to the visible spectrum?

The answer to the question was provided in the year 1800 by the great British astronomer, Sir William Herschel (see frontispiece), in a series of simple but beautifully executed experiments. Herschel was interested in working out a method of viewing the sun to the best advantage through large telescopes. He used various combinations of differently colored dark glasses and was astonished to find that when he used some of them he felt a sensation of heat, though they passed but little light, whereas with others he obtained much light, with scarcely any sensation of heat. As a result of this, it occurred to him that different rays of the spectrum had the power of heating bodies very unequally distributed among them. In an address to the Royal Society in London on March 27, 1800, he hinted that radiant heat from the sun "will at least partly, if not chiefly, consist, if I may be permitted the expression, of invisible light."⁴

The experiments which led to this first hint that the heat rays formed an invisible extension of the visible spectrum were rather imperfect. Herschel therefore made many more observations, and on April 24, 1800, he was able to show definitely to the members of the Royal Society that the spectrum of the sun is continued beyond the red into a region where it is invisible, yet where it exerts a maximum heating effect.⁴

Herschel had discovered the region of the spectrum now known as the "infrared"—meaning "below the red." His method of observation was very simple and consisted merely in passing a thermometer through the spectrum. As the thermometer proceeded from the violet to the red, it registered an increasing temperature, and, when it was placed just beyond the red end, the temperature was still higher. As the thermometer was passed still further away from the red, the temperature reached a maximum, and then slowly decreased. This showed that the heating radiation from the sun extended a considerable way into the infrared and that its maximum effect was in the invisible region just beyond the red. Herschel also placed his thermometer in the invisible region beyond the violet at the other end of the spectrum, the region we now know as the "ultraviolet." He found no increase in temperature there. The ultraviolet actually was not discovered until 1801 by Ritter, who showed that silver chloride was blackened when placed in the invisible part of the

spectrum beyond the visible violet. There is reproduced in Figure 2 an illustration from Herschel's published papers, showing the arrangement which he used in discovering the infrared.⁴

Herschel was naturally very curious to know if the invisible rays of heat were identical in nature with visible light, and he made many experiments to determine this, studying not only the rays from the sun, but also those from artificial sources, such as candles, lamps, and the fire. He found that the rays which occasion heat are subject to the same laws of reflection and refraction as the rays of light. He was worried, however, by the fact that there was a heating effect also associated with the visible spectrum, increasing from the violet to the red, and he tried to find out if the heating effect which accompanied red rays was due to the light of the red rays themselves. In this connection he studied the way in which light and heat were transmitted by various materials, particularly red glass, and the manner in which they were scattered by rough surfaces. He found that they were transmitted in different amounts by the red glass and that heat was not scattered so much as light rays. From these observations, he was forced to the conclusion that the rays of heat and light were different in nature.

Many other scientists interested themselves in this problem, but it was not until 1835 that Ampère was able to proclaim the identity of the rays of light and those of heat. In the years which followed, numerous studies showed that heat rays had all the essential properties of the rays of light, the only important difference lying in their lower refrangibility, a difference which we now ascribe to their longer wavelength.

The end of the visible spectrum in the red is usually taken as about 7,600 Å. Wavelengths longer than this constitute the infrared or heat rays. The region of wavelengths shorter than that of the beginning of the violet is the ultraviolet. But the spectrum does not end with the infrared and ultraviolet. Research has shown that it is very broad in extent and ranges from the cosmic rays, which are exceedingly short, to the very long waves of radio and to others which are even longer. The visible spectrum is but a very small fraction of this wide gamut. The approximate wavelength limits of the chief sections of the known spectrum of radiation are shown in Table II.

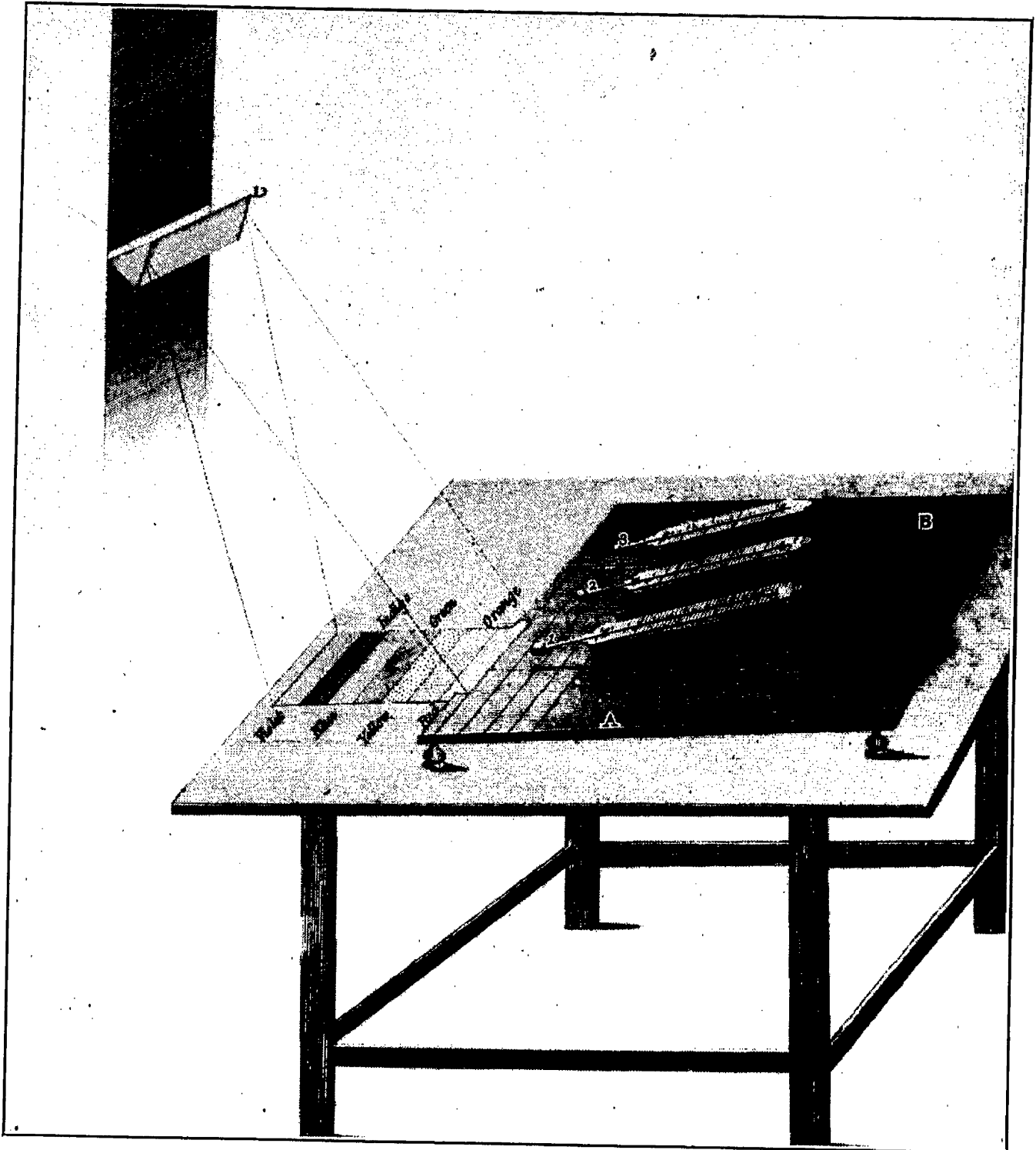


FIG. 2. Herschel's drawing of the apparatus used in the study of the infrared.

This drawing was published with Herschel's second paper in 1800 and is copied from the *Philosophical Transactions* of that year, plate XI, opposite page 292. The spectrum of sunlight produced by a prism was allowed to fall on a table. The nearest thermometer, marked 1, was used to record the increase in temperature beyond the red, while the two other thermometers were used as controls.

TABLE II
THE RADIATION SPECTRUM

<i>Radiation</i>	<i>Wavelength Range</i>
Cosmic rays	0.0002–0.0005 A
Gamma rays of radium	0.005–1 A
X rays	0.1–1,000 A
Ultraviolet	136–3,900 A
Visible	3,900–7,600 A
Infrared	7,600–5,000,000 A
Hertzian waves	1,000,000–500,000,000,000,000 A (0.1 mm to 50,000 m)
Wireless waves	10,000,000,000–500,000,000,000,000 A (1 m to 50,000 m)

It appears that all these radiations are basically the same and that they differ only in the lengths of their waves. The means required to produce them differ, and so do the devices by which they can be detected. As the wavelength changes, so do the properties of the radiations change. The eye is the most convenient detector of radiation in the visible spectrum, although photographic plates and films can be made to respond to all the wavelengths which can be seen, and many instruments known to the physicist, such as photoelectric cells, can be used to record the wavelengths. The photographic plate can be used to detect the ultraviolet and shorter wavelengths and part of the infrared. For wavelengths longer than about 20,000 A in the infrared, it is necessary to use physical instruments such as the bolometer, the thermopile, and the radiometer, while the very long Hertzian and wireless waves can be detected only by electrical means. Part of the infrared can be detected as heat by some of the sense organs of the body. Whereas the eye is able to sort out different wavelengths of visible light by the sensations of color which they produce, the sensory organs responsible for the feeling of heat cannot distinguish between different wavelengths in the infrared. In the study of the spectrum, however, it is important to be able to determine the wavelengths of the radiations which are concerned. This can be done in the infrared both by the physical detectors and the photographic plate or film suitably prepared.

Photography provides a means of recording radiations, and possesses a number of advantages over the eye and physical in-

struments. For example, it yields a permanent record which can be measured and put away for future consultation, and sent to different places for others to study. If long exposures are given, records can be built up of radiations of very low intensity until a visible image is obtained which can be studied. Photography can show clearly transient events which occur too rapidly to be studied in detail by the eye and other detectors. It can record wavelengths to which the eye itself will not respond.

The range of wavelengths which can be recorded by photography in the invisible infrared is about twice as great as the range which the eye can see. It is, however, but a small fraction of the whole range of the infrared, and a still smaller part of the gamut of known radiations. By direct photography at the present time, it is possible to photograph the spectrum out to about 13,500 Å, while by special methods records can be obtained out to about 20,000 Å. Beyond this, physical instruments must be used. It would be unreasonable to suppose that it will not be possible in the future to make plates sensitive beyond 13,500 Å. The handling of such plates would require special technique, however, because the atmosphere absorbs strongly in certain regions beyond this point. There is another factor which would interfere seriously with the preparation and handling of photographic materials sensitive to very long wavelengths. At ordinary temperatures, there is present in space a considerable amount of what may be called "dark space radiation," which is of long wavelength; this would affect plates which were sensitive to it, and probably also would interfere with the chemical reactions involved in the manufacture and handling of the plates. At room temperatures, this radiation could not be ignored, and, if one desired to photograph out to, say, 40,000 Å or beyond, on a plate sensitive to this region, the space radiation would affect the plate in addition to the particular radiation being photographed. The effect of the radiation could be reduced by working at low temperatures, but there are many drawbacks which would render this impracticable (see Chapter V).

It appears, therefore, that progress in infrared photography beyond the present limit must be very slow. At the time of writing, however, infrared photography with the ease of ordinary photography is a relatively new subject, and only the fringe of

its usefulness has been touched. It has been surrounded with all the glamour and charms which the vivid imagination of the popular press is capable of bestowing. It has emerged from it as a proved useful weapon for the practical photographer and the investigator in the fields of science and technology. Further study cannot fail to find new uses for it. It is the purpose of this book to survey what has been done up to the time of writing, and to consider in detail the practical methods and underlying principles, a knowledge of which should aid in the proper application of the subject to the solution of new problems.

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Chapter II

THE GENERAL PRACTICE OF INFRARED PHOTOGRAPHY

There is no fundamental difference between the practice of infrared photography and that in which visible light is used. Anyone equipped for photography with ordinary, orthochromatic, or panchromatic plates or films can make infrared photographs without investing in any extra equipment other than a filter for use on the lens of his camera. Naturally, certain precautions must be taken because of the sensitivity of the materials to the invisible radiations, but these do not involve any unusual practice. In fact, in addition to the filter, the only other thing which the general photographer might wish to purchase is a special infrared darkroom safelight, but even this is unnecessary if it is not an inconvenience to operate in total darkness while loading and developing. If unusual work is to be done, it may be desirable to buy special lenses, plates, and films; to compound particular developers; and so on. It is often necessary to do this for uncommon uses of ordinary photography, however, and so the use of the infrared does not place any unusual demands on the photographer's pocket or skill. It cannot be emphasized too fully that for general infrared photography the equipment and experience acquired in the course of normal photographic practice are perfectly adequate.

The chapters of this book are devoted to the principles and practice of infrared photography in its manifold applications. In order to make the most of the subject one should study these chapters. It is believed, however, that it is of some value to bring together in one chapter a summary of the chief points to be borne in mind in the use of the infrared for general photographic purposes. It is the object of this chapter to present this material in a readily accessible form. References will be made to the other sections of the book where the subjects are treated in greater detail.

INFRARED PLATES AND FILMS

A variety of infrared-sensitive plates and films is available from several manufacturers. They are listed in Appendix I. The selection of the material will naturally depend on the purpose for which it is to be used, and it will be made according to requirements of speed, contrast, and region of sensitivity. These factors are discussed in various places in this book (Chapters IV, V), and therefore are not considered here.

The materials which are in most common use for general infrared photography by amateurs and by professional and commercial photographers are:

Sheet films:

Kodak Infrared Sheet Film.

Roll and miniature films:

Kodak Infrared Film (Miniature and Roll).

Plates:

Kodak Infrared-Sensitive Plates

Kodak (England) I.R.E.R. Extra Rapid Infra-red Plates.

Products of other manufacturers were withdrawn temporarily during the war, but it is understood that some may be reinstated.

Plates and film for general infrared photography require no greater care in storage than do panchromatic materials, although, in common with them, they should be kept cool and dry. Certain of the plates which are used only for spectrographic studies and are sensitive in the far infrared should be kept in an icebox or refrigerator. If plates and films are kept cool in this manner, and it is a desirable practice even if not absolutely necessary, they should be removed the day before they are to be used. If they are not allowed to warm up to room temperature before the package is opened, dew may deposit on them and cause markings.

CAMERAS

Cameras for photography by infrared do not differ in any essential principle from those for ordinary photography. In general, any camera can be used for work in the infrared, al-

though there are a few precautions which must be observed to ensure satisfactory operation. They are concerned with the bellows, the dark slides, the shutter, and the lens.

The camera bellows must not transmit any radiation to which the film responds; otherwise the negative will be fogged when the draw slide is withdrawn. Bellows are usually made of a thin layer of natural or artificial leather containing a black pigment and backed by a sheet of black cloth. Strips of paper are glued between the two layers so as to keep the bellows in shape and to ensure that they fold correctly. The bellows used on most cameras made at the present time are quite opaque to the infrared. If there is reason to suspect fogging due to their transparency, they may be tested by loading the camera with a film, removing the draw slide, extending the bellows, and shining a 100-watt lamp on them from a short distance for about a minute. When the plate or film is developed, lack of safety of the bellows will be shown by fogging of parts of the film, while the edges covered by the rebates of the material holder will remain clear.

It is very important that the film holders and the draw slides should not transmit infrared. One of the most common causes of fogging of infrared materials in old cameras is transparency of the holder or slide. If it is made of wood, it should be suspected immediately, for many kinds of wood are quite transparent to the infrared (see Chapter X). It is, in fact, a good rule to avoid the use of wood in the draw slide and in the backs of single holders. Numerous cases have been recorded where it actually has been possible to make infrared photographs through the wooden slide left in the holder. The fact that a holder is perfectly safe for use with panchromatic materials is no criterion of its safety in the infrared. In general, nothing can be told about the infrared transmission of a material from its behavior toward visible light.

Certain kinds of hard rubber and plastics are also very transparent to the infrared. In fact, hard rubber is often deliberately used to screen off the visible light from a lamp and let through the infrared. Some manufacturers test their hard rubber for its opacity to the infrared before making it up into draw slides and put identifying markings on the slides to indicate that they are safe. For instance, hard rubber draw slides made by Graflex,

Inc., carry five dots embossed on the metal tops if they are satisfactory for infrared use. If there is any reason to suspect that a draw slide is not safe, it may be tested in the following manner: An infrared-sensitive film is put in the dark slide or on the work bench in the darkroom, and covered with a thin piece of metal or photographic black paper in which an aperture of a definite shape is cut. The draw slide is then placed over the plate, and a 200-watt lamp is held over it at a distance of about 3 ft for five minutes, after which the plate is developed in total darkness. If the draw slide is unsafe, an image of the aperture denser than the background will appear.

Occasionally, single holders are supplied which are made of wood and have hard rubber slides. Even though the slide is safe, the holder should be suspected, because the wooden back most likely will let through some infrared.

Material holders and slides made of metal are perfectly safe for use with infrared films. If metal sheaths are used for sheet film in wooden holders, these holders may be used, provided the draw slide is safe.

The blades of camera shutters are sometimes made of thin ebonite or hard rubber. These provide a possible source of fogging. Metal shutter blades are entirely satisfactory.

LENSES AND FOCUSING

The characteristics of glasses and lenses in the infrared are dealt with in some detail in Chapter XVI. It is convenient here merely to mention the precautions which may have to be taken to ensure correct focus in making infrared pictures.

In the early days of photography the materials used were sensitive only in the blue, violet, and ultraviolet, and photographic lenses were so designed that, when they were focused visually, they were also in focus for photography. When panchromatic plates and films became available, a different correction was necessary, since the sensitivity was no longer confined to the short wavelengths. This correction is of minor importance for ordinary photography, but is of significance for cinematography where it is important to have exceedingly sharp focus, and particularly in cases where materials are used which are very sensitive to the red.

The corrections are necessary because in the simple types of lens the position of good focus for one color is not the same as that for other colors. If a subject illuminated by white light is photographed, therefore, the sharp image will be bordered by out-of-focus fringes. The so-called achromatic lenses (anastigmats) are corrected so that wavelengths in the violet and the yellow are both in focus in the same plane. Such lenses are generally perfectly satisfactory for use with panchromatic materials. In photoengraving, and certain other applications where pinpoint sharpness is required for all colors, the lenses are modified still further, so that more wavelengths are in focus. Such lenses are called apochromatic.

As the wavelength departs from that for which the lens is corrected, the focus for it deviates further from the correct focus. In the case of the infrared, this difference of focus may be considerable enough to give out-of-focus pictures when sharp results would be obtained with panchromatic plates and films. Lenses differ in their infrared focus, and it is not possible to draw any general conclusions as to the change in the bellows extension which must be made after focusing visually on the ground glass or by scale. In all cases where a correction is required for the infrared, the lens must be racked out for a distance slightly longer than that necessary for good panchromatic focus. This is equivalent to focusing on a nearer object. The correction is usually small, in most cases much less than one per cent of the focal length. In fact, in a large series of modern lenses tested, the maximum correction was one half of one per cent, and in most cases it did not exceed 0.35 per cent.

The "Data Book on Kodak Lenses" gives the infrared focus corrections for a large group of lenses. In the case of the Ektar group for the Ektar camera, each lens has a focusing mark for infrared. The following corrections for a number of lenses for popular cameras are taken from the Data Book:

INFRARED FOCUSING

1. Kodak Anastigmat Special $f/3.5$, 50 mm (as used on Kodak 35).

Turn focusing scale counterclockwise by 0.25 in.*

* This correction from the visual focus represents a working average for distance settings from 8 ft to infinity.

2. Kodak Anastigmat $f/4.5$, 51 mm, and $f/5.6$, 50 mm (as used on Kodak 35).

Turn focusing scale counterclockwise by 0.17 in.*

3. Kodak Anastigmat Special $f/4.5$, 47 mm (as used on Kodak Bantam).

Turn focusing scale counterclockwise by 0.15 in.*

4. Kodak Anastigmat Special $f/4.5$, 100 mm, 101 mm, and 127 mm (as used on Kodak Monitors and Kodak Vigilants).

Turn focusing scale counterclockwise by 0.16 in.*

5. Kodak Anastigmat $f/4.5$, 103 mm and 126 mm (as used on Kodak Monitors and Kodak Vigilants).

Turn focusing scale counterclockwise by 0.14 in.*

6. Kodak Anastigmat $f/6.3$, 105 mm and 130 mm (as used on Kodak Vigilants).

Turn focusing scale counterclockwise by 0.19 in.*

7. Kodak Ektar $f/3.7$, 105 mm.

Extend lens 0.004 in. (0.1 mm) from visual focus.

8. Kodak Ektar $f/4.5$, 101 mm and $f/4.7$, 127 mm.

Extend lens 0.004 in. (0.1 mm) from visual focus for both lenses.

9. Eastman Ektars $f/6.3$, 8½ in.; $f/6.3$, 10 in.; $f/6.3$, 12 in.; $f/6.3$, 14 in.

Extend lens after focusing critically for visible light by:

0.008 in. (0.2 mm) for Eastman Ektar $f/6.3$, 8½ in.

0.012 in. (0.3 mm) for Eastman Ektar $f/6.3$, 10 in.

0.016 in. (0.4 mm) for Eastman Ektar $f/6.3$, 12 in.

0.031 in. (0.8 mm) for Eastman Ektar $f/6.3$, 14 in.

10. Kodak Anastigmats $f/4.5$, 5½ in.; $f/4.5$, 6¾ in.; $f/4.5$, 7½ in.; $f/4.5$, 8½ in.; $f/4.5$, 10 in.; $f/4.5$, 12 in.

Extend lens from visual focus by:

0.012 in. (0.3 mm) for 5½-in. (no. 31) lens

0.023 in. (0.6 mm) for 6¾-in. (no. 32) lens

0.027 in. (0.7 mm) for 7½-in. (no. 33) lens

0.031 in. (0.8 mm) for 8½- and 10-in. (no. 34 and no. 35) lens

0.047 in. (1.2 mm) for 12-in. (no. 36) lens

11. No. 70 Kodak Anastigmat $f/7.7$, 8 in.

Extend lens 0.016 in. (0.4 mm) from visual focus.

These corrections were derived by taking series of photographs and judging the setting for best focus on infrared and panchromatic film. Table III shows the focus shift for a number of Eastman lenses for aerial photography. The values were derived by photographing a resolving power test object placed at 35 focal lengths from the lens under test, in steps at about 0.3 mm apart. Kodak Aerographic Super-XX Film was used with the Wratten no. 12 filter, and Kodak Aerographic Infrared

Film with the Wratten no. 89A filter. The size of the focus shift is given in millimeters and in focal lengths.

TABLE III
INFRARED FOCUS SHIFT FOR EASTMAN AERO LENSES

<i>Lens</i>	<i>f/No.</i>	<i>Focal Length, In.</i>	<i>Focus Shift, Mm</i>	<i>Focus Shift in Focal Lengths</i>
Aero Ektar	6	24	2.1	3.4×10^{-3}
Aerostigmat	5	12	0.4	1.3×10^{-3}
Aero Ektar	2.5	12	1.1	3.6×10^{-3}
Aero Ektar	2.5	7	0.7	3.9×10^{-3}
Anastigmat	4.5	$6\frac{3}{8}$	0.5	3.1×10^{-3}

Usually the higher the aperture and the longer the focal length, the greater is the focal-length correction, but it is not safe to generalize. Additional sharpness usually will be obtained in the infrared if the lens is stopped down.

If critical work is being done and the shift of focus in the infrared is not known, it is best to calibrate the lens by actually making photographs. Series of exposures should be made of objects at various distances, starting with the position of correct visual focus, or that indicated by the focusing scale. The other photographs in each series should be made by increasing the bellows extension slightly beyond that necessary for correct visual focus.

Some help is obtained if the picture is focused on the ground glass with a red filter on the lens. This reduces the brightness of the image on the glass, and so focusing should be done at full aperture, after which the lens may be stopped down to the value desired. This method is quite satisfactory for occasions when the films used are sensitive only in the near infrared, as is usually the case for landscape and medical infrared photography, and when the lenses are of relatively short focus.

For the most exacting work, lenses specially designed to give sharp focus in the infrared when they are in sharp visual focus are used. These are available from a number of manufacturers, from whom information concerning them may be obtained.

Apochromatic lenses should perform better in infrared photography than any other type, if the exposure is to be made at the

visual focus without correction. They are usually of low aperture and of long focus and so they are of little interest for the ordinary photographer. They should be satisfactory for photo-engraving work, however, since low apertures are generally employed for this.

FILTERS

Infrared plates and films are sensitive to the ultraviolet, violet, and blue, as well as to the infrared. Their response to the short wavelengths is so much higher than that to the infrared that it is necessary to use some means of confining the exposures to the infrared. Otherwise, the photographs will appear just like normal negatives.

The undesired wavelengths are absorbed by a filter placed on the lens of the camera. Filters are of two kinds: (1) Sheets of dyed gelatin, which may be used alone or else cemented between pieces of thin glass; (2) plates of glass which is itself colored. Their characteristics are dealt with in detail in Chapter XVI (p. 418). Various kinds of filter mount to fit all makes of lens are available from manufacturers of photographic apparatus.

The filters most useful for general infrared photography are red in color. If one desires to confine the exposures to the infrared alone and eliminate all visible light, then the filters are obviously opaque, unless the plate has no sensitivity in the visible red. A large range of filters satisfactory for infrared photography is available. For general work, it is necessary to use a filter which absorbs the ultraviolet, violet, blue, and green light, and transmits some of the red and all the infrared. Filters generally are characterized by the wavelength below which they absorb and beyond which they transmit. In Table IV, which gives most of the filters commercially available for infrared photography, these wavelengths are listed. In selecting a filter, it is merely necessary to choose one which transmits in the region of the spectrum in which it is desired to photograph. The plate or film used should be as sensitive as possible in this region.

For infrared photography of landscapes, haze penetration, night effects, photomicrography, copying of documents, and infrared medical photography, the following filters are satisfactory:

Wratten nos. 23A, 25, 29, 70, 89 and 89A; Agfa nos. 42 and 83; Ilford Micro 5, Tri-colour Red and Spectrum Red; Leitz Infra Red filter.

For photography in the dark the following filters are used:

Wratten no. 87; Agfa no. 85; Ilford Infra-red.

For special purposes, where it is desired to confine the exposure to still longer wavelengths, filters should be selected according to the position of their wavelength of transmission as shown in Table IV.

Certain combinations of filters may be used to select the longer wavelengths of the infrared and exclude most of the extreme visible red. A study of the transmission curves of filters given in manufacturers' booklets will enable the reader to select suitable pairs (Chapter XVI, "Bibliography").

The difference between the visual opacity and infrared transparency of a common infrared filter, the Wratten no. 89, is strikingly shown in Figure 3. In the upper part there is reproduced a photograph copied on a panchromatic plate. The middle photograph was copied in the same manner, but the left half of the original was covered with the no. 89 filter, which is almost visually opaque and transmits no light to which the panchromatic plate responds. The bottom photograph was made on a Kodak Infrared-Sensitive Plate through the Wratten no. 88A filter, the no. 89 filter still being in position over the original. The plate responds to wavelengths which are transmitted by the no. 89 filter, and the no. 88A filter has its "cut" at longer wavelengths than that of the no. 89 (see Table IV). The result is that the photograph is made by light which passes freely through the no. 89 filter, so that the original is revealed clearly through it.

Since all filters absorb some radiation to which plates and films respond, it is necessary to increase the exposure when filters are used, as compared with that necessary when they are not used. The so-called "filter factor" usually applied represents the number of times by which the correct exposure without a filter must be multiplied to get the correct exposure when a filter is used. The filter factor has no significance in the case of infrared materials, because infrared films are not used without a filter. It is

TABLE IV
FILTERS FOR INFRARED PHOTOGRAPHY

<i>Manufacturer</i>	<i>Name and Number of Filter</i>	<i>Wavelength beyond Which Filter Transmits (in Å)</i>
Eastman Kodak Co. Kodak, Ltd. (Wratten filters)	Wratten 23A	5,600
	" 25	6,000
	" 29	6,200
	" 70	6,700
	" 89	6,800
	" 89A	7,000
	" 88	7,200
	" 88A	7,400
	" 87	7,700
	Special, Batch 5233	About 9,200
Agfa	Agfa 42	6,000
	" 83	7,250
	" 84	7,500
	" 85	8,300
	" 87	8,400
	" 89	About 9,300
Ilford, Ltd.	201	5,600
	202	5,800
	204	6,000
	205	6,300
	206	6,600
	207	7,600
	207 + 813	8,000
Carl Zeiss (glass)	Infra-red (combination of Schott glasses RG5 and BG3)	7,500
Defender	30-R	5,700
	40-R	5,900
	50-R	6,100
	100-R	6,900
Corning Glass Works (glass)	246	5,800
	245	6,000
	244	6,100
	243	6,200
	242	6,300
	241	6,400
	244 + 555	6,900
	244 + 585	7,100
	254	7,800
	255	7,600
Bausch and Lomb (glass)	R1	5,900
	R2	6,000
	R3	6,100
Chance Bros. (glass)	3, Deep Orange	5,500
	2, Red	6,000
	1, Ruby	6,400
Schott (glass)	RG1, 2 mm	6,000
	RG2, 2 mm	6,300
	RG5, 2 mm	6,700
	RG8, 2 mm	7,000
	RG7, 2 mm	About 9,000



FIG. 3. Photographs illustrating the visual opacity and infrared transparency of a deep-red filter (*see* p. 19).

the custom, therefore, to denote the exposure required with a particular combination of plate or film and filter, as compared with the exposure which would be necessary to give a good negative on a fast panchromatic or orthochromatic film without a filter. Exposure values obtained in this way are generally given on the instruction sheets issued by photographic manufacturers.

Since there is usually a gap in the spectral sensitivity of infrared materials from the middle of the green to the middle of the red, all filters which have their transmission threshold in this region will require the same exposures. If a filter cuts out some of the red or infrared to which a material responds, however, it will be necessary to give a higher exposure than for a filter which does not behave in this way. For instance, with Kodak Infrared Film, exposures will be the same through the Wratten filters nos. 25, 29, and 70. On the other hand, it will be necessary to double the exposure if the Wratten no. 87 filter is used, because this absorbs the red radiation to which the plates respond.

SOURCES OF INFRARED

All the light sources commonly used for normal photography are satisfactory for general infrared work. No special sources, such as those recommended for therapeutic treatment, possess any advantages. The photographer who is provided with standard studio lighting equipment can make infrared photographs without any change in his equipment beyond the provision of a filter. For taking photographs in total darkness, it is necessary to provide filters over the light sources, in the manner described in Chapter XII (p. 318). The characteristics of all the sources available for work in the infrared are discussed in detail in Chapter VII, and special applications are dealt with there. A summary of light sources for the various purposes is given on p. 173. In the following, mention is made of the sources most readily available for general infrared photography:

Outdoor work: sunlight.

General photography, portraiture, medical work, copying, etc.: sunlight, tungsten-filament lamps, Photoflood and Movieflood lamps, carbon arcs, Photoflash lamps.

Cinematography: sunlight, all types of studio arcs, and tungsten-filament lamps.

The reflectors of silvered glass and metal used for ordinary photography are perfectly satisfactory for use in the infrared. A diagram showing a suitable arrangement of lights for copying and general infrared photography is given in Figure 4. Another arrangement, with exposure data, is given in Chapter IX, p. 235.

EXPOSURE

The exposure meters commonly employed for normal photography do not respond to the infrared. They are not of value for

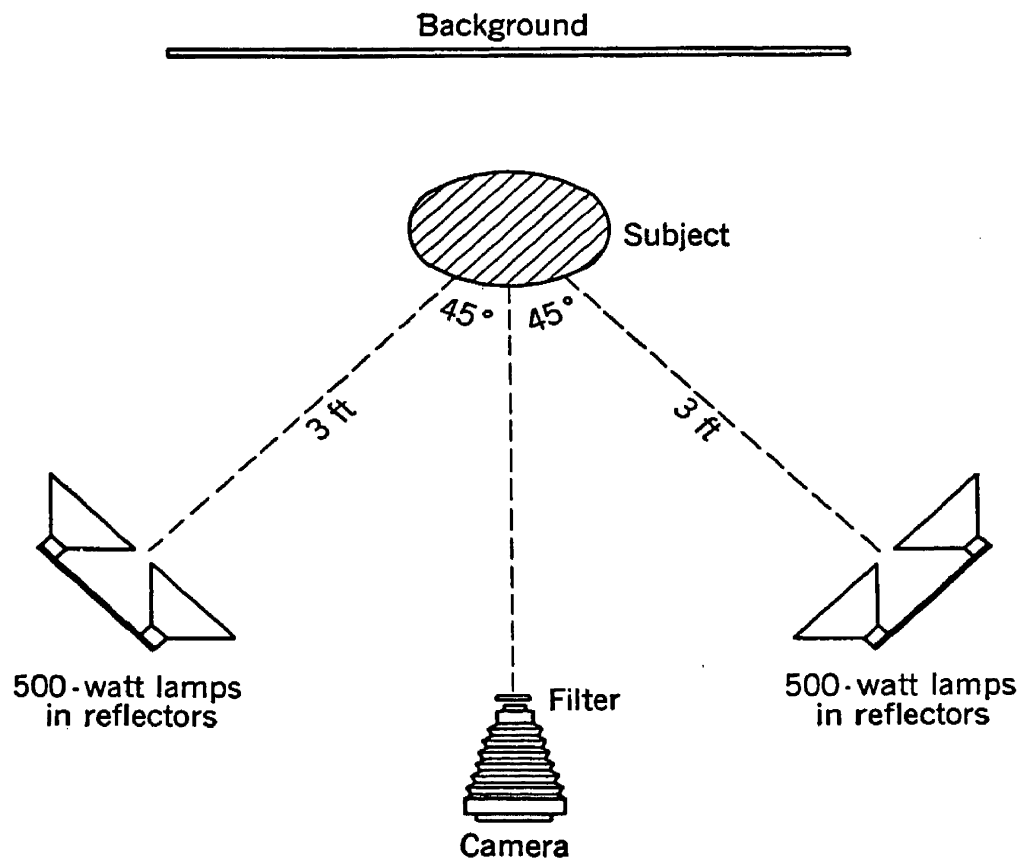


FIG. 4. Simple arrangement of lights and camera for infrared photography of general subjects.

The lights are arranged to illuminate the subject as flatly as possible.

determining exposures by daylight, because there is no fixed relationship between the infrared content of daylight and the intensity of visible light. In the case of artificial light sources, however, it should be possible to use exposure meters with suc-

cess, since the ratio of visible to infrared radiation is constant.

As a guide to the exposure of the infrared materials most commonly used for general photography, the data in Table V have been selected from manufacturers' instruction sheets.

TABLE V

EXPOSURES FOR INFRARED PHOTOGRAPHY

Subject: Open Landscape, Summer Sun; Close-Ups, Bright Sun

<i>Material</i>	<i>Filter</i>	<i>Exposure</i>
Kodak Infrared Film (Miniature and Roll)	Wratten no. 25, 29, or 70 Wratten no. 88, 89, or 89A Wratten no. 87 or 88A None	$\frac{1}{25}$ sec, $f/8$ $\frac{1}{25}$ sec, $f/6.3$ $\frac{1}{25}$ sec, $f/5.6$ $\frac{1}{100}$ sec, $f/11$
Kodak Infrared Sheet Film	Wratten no. 25, 29, or 70 Wratten no. 87 or 88A None	$\frac{1}{25}$ sec, $f/8$ $\frac{1}{25}$ sec, $f/5.6$ $\frac{1}{50}$ sec, $f/16$
Kodak Infrared-Sensitive Plates	Wratten no. 25, 29, or 70 Wratten no. 88, 89 or 89A Wratten no. 87 or 88A None	$\frac{1}{25}$ sec, $f/6.3$ $\frac{1}{25}$ sec, $f/5.6$ $\frac{1}{25}$ sec, $f/4.5$ $\frac{1}{100}$ sec, $f/11$
Kodak (England) I.R. E.R. Extra Rapid Infra-red Plate	Wratten no. 88A	$\frac{1}{50}$ sec, $f/8$

In photographing small specimens where the camera bellows must be extended considerably, the effective aperture is markedly less than that indicated on the lens. At unit magnification, the lens-to-film distance is twice the focal length, and the effective f -value is twice the rated value. For example, if the diaphragm is at $f/8$, the actual working aperture is $f/16$. This means that four times the exposure must be given that would be used if the lens were really working at $f/8$. If the total bellows extension is about one and one half times the focal length, the exposure should be about doubled. No allowance need be made for objects no nearer than 3 or 4 ft. The effective f -value for all

close-up work can be computed from the formula:

$$\text{Effective } f\text{-value} = \frac{v \times f}{F}$$

where v = lens-to-film distance, or focal length plus extension from infinity focus,

f = indicated f -number of aperture, and

F = focal length

Various portrait attachments and supplementary lenses are provided for some cameras. When they are used, it is not necessary to make compensation in exposure for close-up work, since the effective f -value remains unchanged. For the best definition, however, the lens should be stopped down to $f/11$ or $f/16$.

DARKROOM PRACTICE

There is no basic difference in the handling of infrared films and the panchromatic variety. The chief point to be borne in mind is that the infrared cannot be seen, so that care must be taken to ensure that safelights, wrapping materials, and the like, do not transmit it. Special safelights are available for use with infrared materials (see Chapter XVI for full details). If they are not at hand, all operations requiring exposure of the materials in loading, developing, and so on, should be carried out in total darkness. The photographer would be well advised, however, to obtain an infrared safelight, such as the Wratten Safelight, Series VII, since it is much more convenient to have some illumination in the darkroom. It should be remembered that these safelights are not safe for use with the modern type of highly sensitive orthochromatic and panchromatic plates and films. They must always be changed for an appropriate safelight when these materials are to be handled. Conversely, panchromatic safelights are not safe for most infrared plates and films. Although the green light which they transmit will not affect the materials, they do transmit infrared radiation very freely.

No special developers are required for work in the infrared. Those employed for other photographic plates and films are suitable, although wherever possible the formulas recommended by the manufacturer should be used. Useful formulas are given in Appendix III.

The subject of darkroom practice is dealt with fully in Chapter III, to which reference should be made if greater detail is required.

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Chapter III

PHOTOGRAPHIC DARKROOM PRACTICE

THE PHOTOGRAPHIC DARKROOM

The operations of loading and unloading plates and films, developing them, and making prints and enlargements, are carried out in the photographer's darkroom. The quality of negatives and prints can be influenced very materially by the handling which they undergo in preparation, and it is therefore well worth while to spend some effort to ensure that the arrangements in the darkroom permit of the greatest convenience in handling the photographic materials, and to avoid defects which may result from bad handling. It will not be out of place in this book to give an outline of factors which should be borne in mind in the construction of a darkroom.

Darkrooms are of two kinds. There are those often used by the photographic amateur, in which the room was built for some other purpose, such as a bathroom or kitchen, and was transformed temporarily or permanently for photographic use. In such cases, there is little flexibility in the choice of the size and shape of the room, the nature of the floors and walls, and the plumbing. The other kind of darkroom, which is used at least by professional and commercial photographers and in laboratories, is specially built and equipped for its purpose. It is not the intention here to deal with the multitude of ways in which the amateur can adapt the bathroom or the kitchen. It will be assumed that a room is to be specially designed for photographic purposes, and the sink and bathtub operators should endeavor to follow the principles as closely as conditions will permit.

In the designing of a darkroom the factors of importance include cleanliness, maximum intensity and safety of illumination, and convenience and efficiency in handling photographic materials. The darkroom never should be larger than is necessary for the volume of work to be done, the number of people work-

ing at any one time, and the amount of equipment to be used. All appliances should be so arranged as to facilitate ease of working, and storage places should be provided for all apparatus and photographic materials not in use. As soon as possible after use all apparatus should be cleaned and put away. Walls should not be painted black; that is an old-fashioned idea. They are best painted light grey, green, or white, with a semiglossy paint which can be washed easily. If chemicals are liable to be splashed on the wall, a chemically resistant paint should be used.

FLOOR. The floor should be of a material which can be washed easily. Wooden floors can be covered with roofing paper on which hard rubber tiles are laid down with a waterproof cement. The surface of a concrete or cement floor may be waterproofed by being covered first with three strips of asphalt-impregnated fabric, and then with two layers of reinforced concrete. Hard mastic, consisting of a mixture of asphalt, pea stone, and sand, is the most chemically resistant covering for a concrete floor, but it has the disadvantage that it tends to soften in hot weather and under pressure of heavy objects. Special precautions are required if large heavy tanks are to rest on the floor. For details of construction in such cases the reader should refer to "Photographic Chemicals and Solutions," by Crabtree and Matthews,² "Materials for the Construction of Photographic Processing Apparatus," by Crabtree, Matthews, and Muehler,³ and "Commercial Photofinishing," by the Eastman Kodak Company.⁶

SINKS. The construction of the sinks is of considerable importance. They obviously should be of sufficient size. The tendency in amateur darkrooms is to make the sinks rather small, and as a result operations are a little cramped. Hot and cold water should be available. Sinks are best made of Alberene stone (a selected grade of soapstone; some grades of soapstone tend to corrode rather rapidly), but enameled iron and wooden sinks covered with lead sheeting with burned joints are very satisfactory. In the case of stone sinks the bottom may well be covered with corrugated rubber matting. A grid of wooden slats is often placed in the bottom of a sink. This is best made of wood of triangular cross section, arranged with the apices uppermost so that there is no tendency for the water from a running

tap to splash out of the sink. Compartments for the storage of trays and dishes are very convenient if built under the sink.

WORKING BENCH. There is considerable choice available for materials for the top of the working bench next to the sink. It is best constructed of hard wood, well waxed, and it may be covered with linoleum. Hard rubber sheets cemented to the bench tops with waterproof cement provide a good covering. Sheets of opal plate glass have sometimes been used as bench tops. They are easy to clean and resist the attack of chemicals. Part of such a top may be covered with a rubber mat.

DRYING CABINET. The best way to dry plates and films is in a specially designed cabinet through which air can be blown by means of a fan. In order to prevent dust settling on the wet plates and films, the air should be passed through a cloth filter. The rate of drying can be accelerated by warming the air by means of electric heating coils which are best arranged so that several degrees of heating can be obtained by means of a series of switches. The air may be blown through the drying cabinet in an upward or downward direction, although the latter is to be preferred. If a vertical movable baffle plate is installed inside, the size of the inner compartment may be varied so as to control the velocity of the air current. Racks should be provided to hold plates inclined at about 30–45° from the vertical, while films should be suspended by clips or hangers. Long films, such as roll films or 35-mm film from miniature cameras, should be provided with heavy clips at the bottom so that they do not curl.

TANKS AND TRAYS. Plates and sheet films are developed in flat dishes or trays of porcelain, glass, enameled iron, Inconel, stainless steel, papier-mâché, or wood, impregnated with wax or coated with an asphalt paint, or else in special tanks. Many kinds of metal and hard rubber tanks are available on the market and are described in the catalogues of all photographic supply houses. They are sometimes provided with grooved metal holders which will accommodate a dozen plates or films, vertically and separated from one another, or else with separate hangers for individual plates or films. When many are to be developed, tanks are preferable to trays, since many more plates or films can be treated at one time with equal agitation and equal times of development.

One may develop long films one at a time in trays by holding each film at both ends and forming a loop which is passed back and forth through the developer from one end of the film to the other. They may also be developed in tanks. Some of the tanks permit loading and development of the films in daylight. In the case of others, loading has to be done in the darkroom, but the loaded tank can be carried into the light for the time of development. For developing miniature-camera negatives, small drums are sometimes used. The films are wound on them, and they are then rotated in a tank or tray of developer. With the tray method, and using the types of tank just mentioned, only one film can be treated at a time. In the photofinishing industry large numbers of films must be handled simultaneously, and so large deep tanks are employed. The films are provided with weighted clips at the bottom which cause them to hang vertically, and with hangers at the top which permit many films to be suspended from rods placed across the tanks. Films in the form of cut sheets are developed in the same way as plates in a tray or dish if they are few in number, or else in special hangers in a tank.

Film tanks and trays may be made of any of the materials mentioned in connection with plates.

SAFELIGHTS. Proper illumination of the darkroom is a matter of first importance. As far as possible, darkrooms should not be dark, but should be provided with as much light as possible, provided it does not fog the film in a reasonable time. In certain cases, however, complete darkness is desirable. The characteristics of so-called "safelights" for darkroom illumination is treated in some detail in Chapter XVI. It is sufficient to say here that, if it is possible, the lamps used in the darkroom should be provided with colored filters which do not let through light to which the plates and films respond. In the case of panchromatic materials which respond to light of all visible colors, the proper filter transmits a very small amount of light in the green part of the spectrum to which the eye has its maximum sensitivity. Infrared plates and films are always sensitive to the blue and part of the green, and sometimes to part of the red. In addition, of course, they respond to the infrared. The safelight for use with such materials will thus absorb strongly in the in-

frared, and also in the other parts of the spectrum to which they are sensitive. The filter will generally be green in color, resembling visually those employed with panchromatic materials. It should be borne in mind, however, that panchromatic safelights usually transmit the infrared very freely, so that they cannot be used with infrared materials. Only those specially made for the purpose, such as the Wratten Series VII, should be used, if it is undesirable to work in total darkness. If there is any doubt at all about the safety of a safelight, it is better to work in total darkness, or to make a test of the safety of the safelight in the manner described in Chapter XVI.

In general, safelights will be provided to give general illumination to the darkroom, to give particular illumination to the working space, and sometimes to provide a safe illuminator by which the progress of development may be judged by inspection of the plate or film. Safelights for the first purpose will usually be overhead and suspended from the ceiling. They may be of the direct or indirect style; that is, they may shine downward, so that their light falls directly on the floor and working space, or they may shine upwards so that the room is illuminated by the light reflected from the ceiling. To provide light directly on the sink and bench, safelights may be suspended a few feet directly above them, or attached to the wall. Wall safelights serve also as viewing boxes for the inspection of the negatives during development.

It is sometimes convenient to be able to view the negative by white light as soon as it is fixed. This may be done conveniently by attaching a white-light illuminator to the wall and providing a foot switch under the bench for working it. This type of switch is an advantage in that it leaves both hands free for handling the negatives, and also eliminates the need for drying the hands.

TIMERS. Clocks or timers of various kinds are available for darkroom use and are very necessary since the bulk of development is carried out at the present time by the time and temperature method. The time of development for a given contrast with a particular plate or film is determined by the temperature of the developer. It is customary, therefore, to measure the temperature of the solution and then develop for the appropriate time. It is convenient to provide a separate small safelight lamp

for illuminating the timer, shielding it so that no direct light falls on the place where plates and films are being handled. A thermometer should be available in the darkroom, somewhere over the sink or bench, so that it can be found in the dim light.

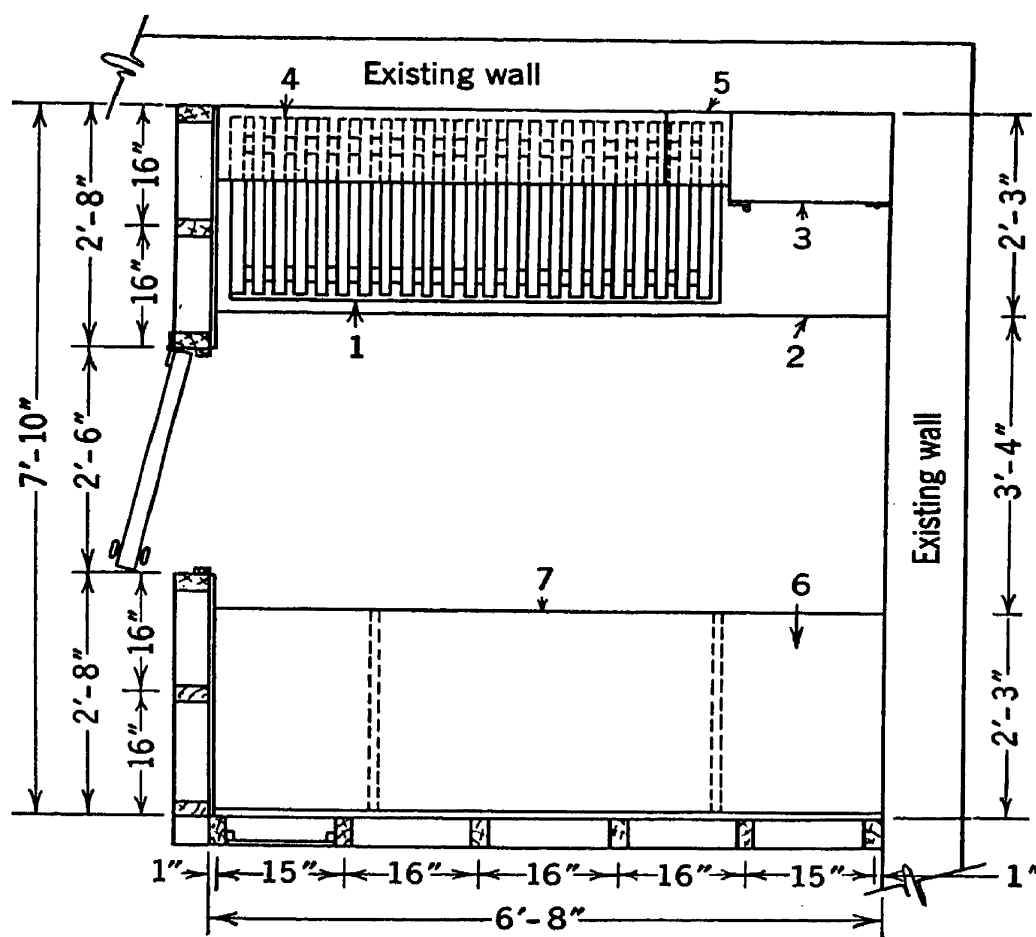
Shelves should be built over the sink and bench to carry the stock solutions of developer and fixing bath, measuring glasses, and other auxiliary apparatus.

VENTILATION AND TEMPERATURE. Every darkroom should be well ventilated. Proper air circulation ensures comfort and greater efficiency of the occupants of the room. If the darkroom is liable to be uncomfortably cold in winter, some means of heating should be provided. If an electric or other luminous heater is employed, care should be taken to see that no light enters the working part of the room.

Refrigerating units of small size are available at reasonable cost, and it should be possible to use them for controlling the temperature of the air in darkrooms, and for providing ice for cooling solutions in hot weather. Control of the temperature of photographic solutions is very important. By means of supplies of hot and cold water from faucets, passed through some kind of mixing device, water at any desired temperature can be made available and used for bringing the temperature of the solutions to the right level. A container should be at hand to fill with water of the desired temperature. The bottles, tanks, trays, and dishes containing the solutions can be immersed in this water until they have reached the correct temperature. If the highest degree of temperature control is desired, and a certain expense can be afforded, it is best to provide a large thermostat tank of water, accurately controlled by one of the many common means, and to keep all the trays or tanks of solution in this bath while they are being used.

WATER. Ordinary tap water is commonly used for washing the developed negatives. Various types of washers are available commercially, or washing may be done by letting water flow through the tray or tank containing the negatives, or by changing the water many times at intervals of about five minutes. In washing, it is important that the salts which have diffused out of the negative should be carried away and be replaced by fresh water as quickly and efficiently as possible. This can be achieved by

rapidly circulating fresh water over the plates or films or by replacing the water very frequently. A good rule for washing films and plates is to wash them for half an hour in such a manner that the water in the vessel is replaced completely once every five minutes.

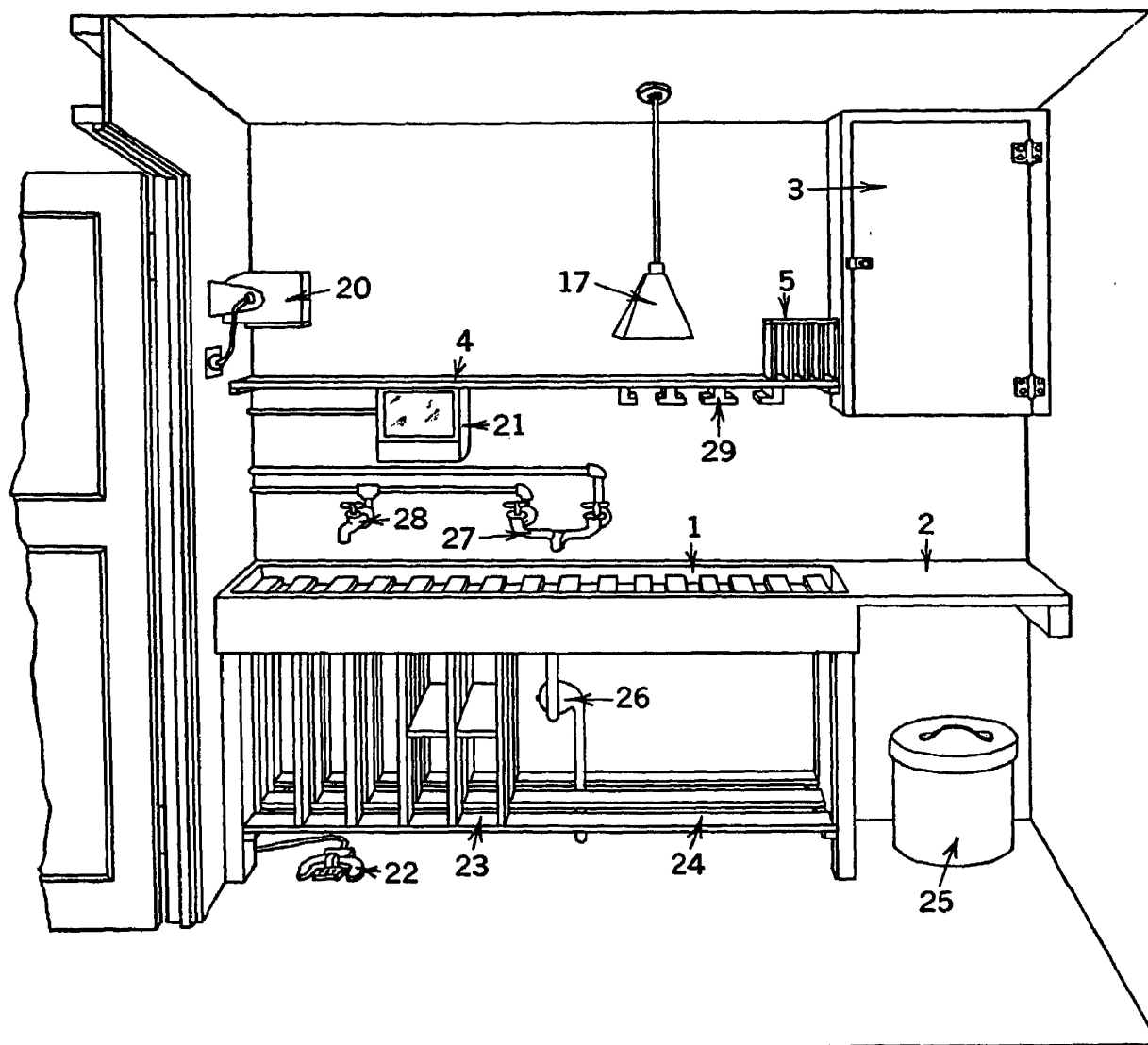


A. Plan of darkroom.

FIG. 5. Diagrams showing arrangement of a darkroom for negative developing and printing.

(Courtesy Eastman Kodak Co.)

PRINTING DARKROOM. The discussion so far applies primarily to the handling of negative materials. The technique of handling printing papers does not differ in any basic manner from that for negatives. In the printing darkroom it is usual to have the printers and enlargers. If prints are handled in a separate room from negatives, this room should be provided with safelights suitable for the manipulation of printing papers. These are much lighter than the safelights for negatives. Precautions should be taken to prevent white light from the enlarger or printer from falling directly on undeveloped paper. The supply of paper to

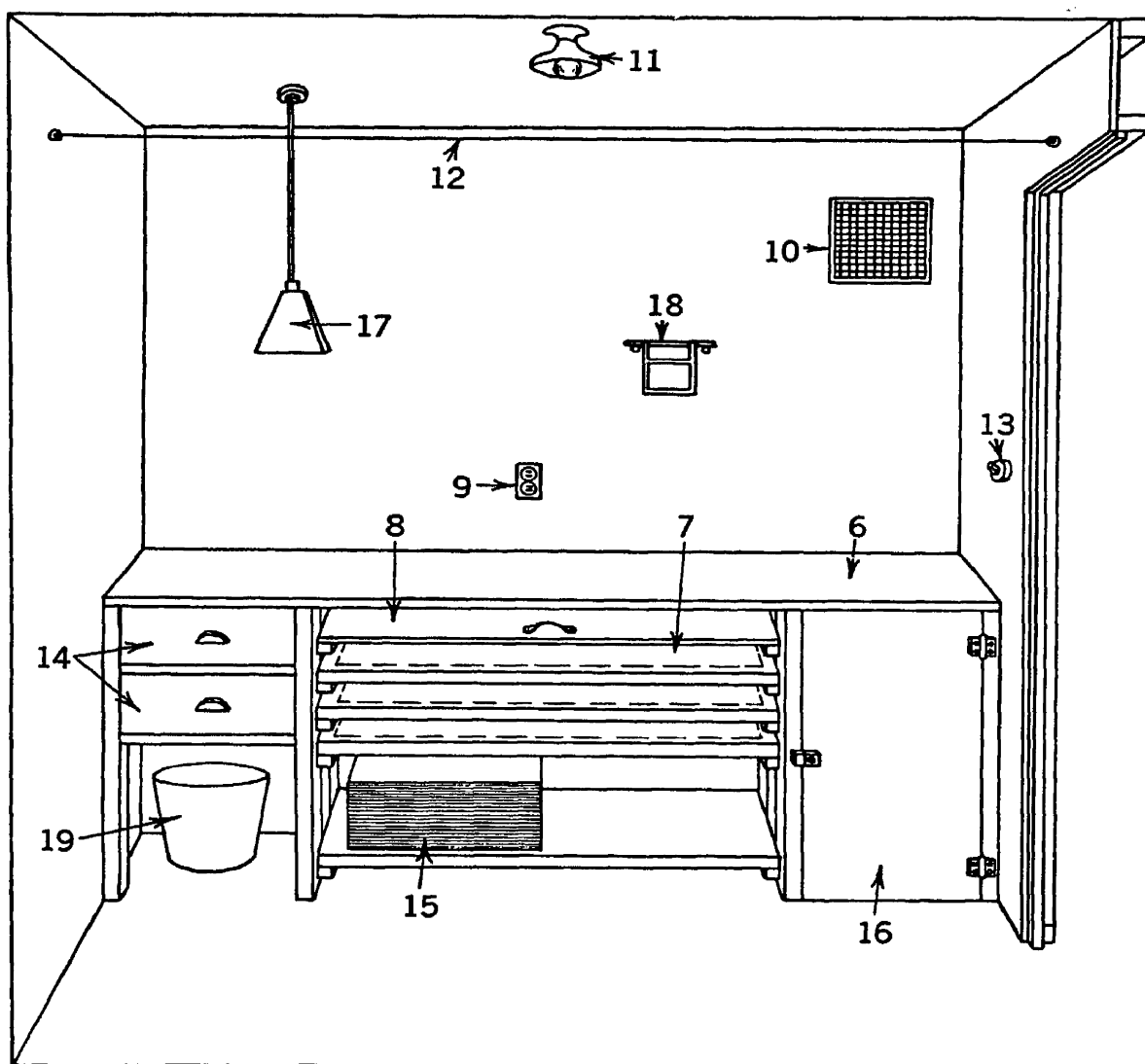


B. Elevation of negative developing bench.

FIG. 5 (Continued).

be used in printing should be kept in a drawer or other container with a light-tight lid which can be opened simply for easy removal of a sheet of paper and closed before the printing light is turned on. If the printing is done in the same room as negative development, it is necessary to provide two sets of safelights, and printing should not be done while negatives are being developed unless a light-tight cover is provided for the developing tray or tank or a daylight developing tank is used.

Prints usually require longer and more efficient washing than films or plates, because it is necessary to remove the hypo from the paper as well as the emulsion. Care should be taken to ensure that the prints are kept in circulation during washing so



C. Elevation of printing and enlarging bench.

FIG. 5 (Continued).

The following is a key to the numbers in Figures 5A, 5B, and 5C:

- | | |
|---|---|
| 1. Sink. | 16. Storage cabinet. |
| 2. Work bench. | 17. Safelight lamp. |
| 3. Chemical-storage or negative-drying cabinet. | 18. Film- and plate-developing hangers. |
| 4. Shelf. | 19. Wastepaper basket. |
| 5. Safelight-storage rack. | 20. Safelight lamp. |
| 6. Printing and enlarging bench. | 21. Safelight lamp with opal glass for viewing. |
| 7. Print-drying racks. | 22. Foot switch for viewer. |
| 8. Dust cover for drying racks. | 23. Tray-storage racks. |
| 9. Electric outlet. | 24. Bottle-storage rack. |
| 10. Ventilator with light trap. | 25. Can for waste. |
| 11. White ceiling light. | 26. Drain. |
| 12. Film-drying wire. | 27. Mixer. |
| 13. Switch for white light. | 28. Cold-water tap for washing. |
| 14. Drawers. | 29. Rack for measuring glasses. |
| 15. Blotters. | |

that no two overlap for any length of time. Washing tanks and trays for prints are usually larger than those for negatives. Their use is described in textbooks of practical photography. A good rule for paper prints is to wash for one hour in such a manner that the water in the vessel is replaced completely once every five minutes. Prints wash more slowly in cold water than in warm water. Whenever possible, the temperature of the wash water should be maintained between 65 and 70° F. For greatest permanence, and when complete removal of hypo is important, each print, after being washed for 30 minutes, should be immersed for about 6 minutes in a dilute peroxide-ammonia solution, and finally washed about 10 minutes before drying.

For drying contact prints and enlargements, some sheets of lintless blotting paper should be available to remove surface drops and surplus water, and the prints may then be put to dry on muslin stretched on light wooden frames. If the prints are to be glazed, they are squeegeed on to ferrotype sheets to dry.

LAYOUT OF DARKROOMS. In order to assist the photographer in the design of his darkroom, plans are given for a combined negative developing and printing room (Figure 5).

Figure 5A shows the plan of the combined darkroom; Figure 5B represents the elevation of the negative developing bench; Figure 5C shows the elevation of the printing and enlarging bench on the opposite side of the room. Further details on darkroom design and on the equipment for various users have been discussed by Parker.^{8, 9}

PHOTOGRAPHIC SOLUTIONS

THE MIXING OF PHOTOGRAPHIC SOLUTIONS

Most of the developers, fixing materials, and other chemicals used in treating photographic plates and films are available in the dry form, packed in tins or packages. For use it is merely necessary to dissolve them in water according to the instructions given by the manufacturer. If the photographer desires to mix his own chemicals, he should use only those purchased from reputable manufacturers. The mixing room preferably should be separate from the darkroom, in order to prevent trouble due to chemical dust settling on moist plates or films and so causing spots.

The scales used for weighing photographic chemicals should be selected according to the amount of material to be handled. For the user of small quantities a scale weighing 4 or 5 oz (120–150 grams) is satisfactory while the user of large amounts may require a scale weighing several pounds. The avoirdupois system has been used largely by photographers for many years and is still common in English-speaking countries. The simpler metric system is used in scientific laboratories and is coming into greater general use. A useful conversion table from metric to avoirdupois is given at the end of this book in Appendix II, p. 446. For measuring solutions, various kinds of graduates and measuring vessels are available from dealers in chemical and photographic apparatus.

Photographic solutions should always be mixed according to the directions of the manufacturer of the material for which the formulas are designed. It is important that the given order of the chemicals be followed in dissolving them, and finally water should be added to bring the volume up to the desired amount. Most photographic solutions may be prepared with water at a temperature of 70–80° F (21–27° C), but dissolution is effected more rapidly at 125° F (52° C). If a higher temperature is used, it takes longer to cool the solution to the working temperature of 65 or 70° F (18–21° C), and the rate of solution is only slightly greater.

For a complete discussion of the methods of mixing and using photographic solutions, the photographer should consult the books, "Photographic Chemicals and Solutions," by Crabtree and Matthews,² and "Elementary Photographic Chemistry," by the Eastman Kodak Company.⁴

It is good practice to filter all photographic solutions before use in order to remove particles of dirt and other foreign matter which later might settle on the plates or films and produce spots. This can be done very easily by using several thicknesses of muslin held in place in a glass funnel. If the water supply contains much organic matter, it may be desirable to install a filter on the faucet. Several types of filter are available commercially, one of the most useful consisting of a vessel fitted with a wire screen and felt pad at each end, and filled with fine sand. Where possible, distilled water should be used.

The choice of vessel used for mixing solutions may be left to the photographer, the factors of importance being the size and the use of material which is not attacked by the solution being mixed. Jugs or pitchers of glass, porcelain, or enameled iron are suitable for small amounts of developers and fixing baths. Pails of stainless steel, enamel or hard rubber, or glazed stoneware crocks are satisfactory for larger volumes. After they are dissolved and filtered, the solutions may be stored in glass bottles or chemical stoneware crocks. Rods for stirring the solutions should be of glass, stainless steel (18-8), or hard wood. The storage vessel should preferably be provided with a hard rubber tap or a glass tube syphon. A convenient method of attaching the hard rubber tap to the tank consists in inserting the rubber stem through a soft rubber stopper. The stem and stopper should be secured firmly to the spout of the tank with a stainless-steel or Inconel clamp. Stainless steel (18-8 Mo) is a very satisfactory material for the construction of all vessels for use with photographic solutions except those which are strong oxidizers, such as some photographic reducers.

USE OF PHOTOGRAPHIC SOLUTIONS

DEVELOPERS. The choice of developer will be determined by the nature of the plate, film, or paper, and the contrast and photographic quality desired. Wherever possible the formulas recommended by the manufacturer should be employed, since they have been worked out to give the best results with the materials in question. A number of good developer formulas for general use are given in Appendix III, p. 448.

The borax-MQ (D-76) is an excellent developer for negatives where good tone quality and low contrast are desired. For average contrast, DK-50 is good. For high contrast, the D-19 formula has proved very satisfactory. A useful developer for papers is that given as D-72.

STOP BATHS. It is desirable to use a stop bath between development and fixation. A rinse in plain water is preferable to nothing, but a solution of chrome alum (formula SB-3) provides a satisfactory stop bath for negatives and an acetic acid solution (formula SB-1) for prints. Stop baths immediately neutralize the alkali of the developer carried over by the plate, film or

paper, and so prevent stains and scum, and delay exhaustion of the fixing bath. In addition, the chrome alum bath hardens the negative and is particularly suitable for use in hot weather.

FIXING BATHS. Although a plain solution of sodium thio-sulphate (hypo) of 20–40 per cent strength is a very effective fixing bath, it is best to use an acid-hardening fixing bath. A suitable formula is F-10 in Appendix III, p. 451.

It is standard practice to develop most negative and positive materials at 68° F (20° C), and any great departure from these temperatures means that the likelihood of trouble is increased. As the temperature rises, the developer fogs sooner, blisters are more likely to form in the rinse or fixing baths, and stains may be produced. It is important, therefore, to control the temperature carefully. All solutions used successively, and the wash water, should be at the same temperature if reticulation is to be avoided.

The importance of agitation of photographic materials during processing cannot be stressed too strongly. Convection currents are set up in a developer as a result of the formation of reaction products in the solution. If the solution is not moved about, these reaction products tend to restrain development locally. Agitation will largely offset this effect and also prevent formation of developer mottle. Agitation also speeds up development.

More rapid removal of the developer from the plate or film results when it is agitated on immersing in the rinse bath, and the formation of scum and stains in the rinse and fixing baths also is avoided by agitation.

Numerous devices have been proposed for ensuring the maximum uniformity of development over the whole area of a plate. Rocking of the tray or dish does not usually give good uniformity. The simplest method is to brush the plate during development with a wide flat long-haired camel's-hair brush. About one stroke per second should be given in each direction.

SPOTS AND MARKS

Most of the markings and stains occasionally produced on plates and films during processing may be avoided by observing three simple rules:

1. Maintain the temperature of all solutions as near 68° F (20° C) as possible.

2. Discard a solution as soon as it shows signs of becoming exhausted.

3. Agitate all materials when first immersing in any bath and at intervals during treatment.

A few examples of typical markings which can be prevented by following these rules may be of interest.

AIR BELLS. Bubbles of air, trapped at the film surface, prevent access of developer to the emulsion and cause white spots in the fixed-out material. If the plate or film is immersed slowly in the developer and agitated vigorously as soon as immersed, such markings can usually be avoided.

Scum formation should be guarded against carefully, because even the slightest trace of a surface deposit is picked up when the plate or film is immersed in the solution. A typical scum marking may be caused by the silver salts in the bath reacting with traces of hydrogen sulphide gas in the air, forming silver sulphide, which floats on the surface and is picked up by the films. Every tank containing developer or fixing bath should be skimmed each morning with a strip of blotting paper, or a few layers of cheesecloth on a frame so that traces of scum may be removed.

BLISTERS are caused by the formation of gas bubbles within the gelatin film, when the plate or film is transferred from the developer to the fixing bath. The gas forms when the acid of the fixing bath reacts with the carbonate of the developer. If the gelatin is strong enough to withstand the disruptive action of the gas, no blisters will form, but, if the gelatin is swollen and in a soft condition, the membrane will burst, leaving a tiny pit. Blisters may largely be prevented by maintaining the temperature of the solutions around 68° F (20° C), by rinsing the film thoroughly in water between developing and fixing, and by agitating the film when it is first placed in the fixing bath.*

* The nonblistering alkali, Kodalk, sold by the Eastman Kodak Company, has the advantage over carbonate that it does not generate a gas when added to an acid solution. Blisters therefore may be eliminated if developers containing this alkali are used.

TEAR DROPS OR DRYING MARKS. If drops of water are left on the film during drying, and especially if the drying temperature is excessive, the gelatin does not shrink uniformly, and markings are produced. If plates and films are wiped carefully with a soft sponge or chamois, and allowed to drain a few minutes before the drying air is turned on, formation of these markings can be prevented.

Photographic troubles will be few, and costly retakes largely avoided, if the user of photographic solutions will purchase pure chemicals, mix them according to directions, maintain temperatures at 65–70° F (18–21° C), replace used baths before they become overworked, and agitate films, plates, and papers sufficiently when immersing them in any solution.

Trays, tanks, film hangers, and all other equipment should be cleaned regularly and kept in a definite place when not in use. Dry chemicals and stock solutions should be kept covered to prevent access of dust.

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The books on general practice listed at the end of Chapter II should be consulted also.

Chapter IV

CHARACTERISTICS OF PHOTOGRAPHIC MATERIALS

A photograph consists of a deposit of black silver known as the image, distributed in such a manner as to represent the tones of the subject. To the eye the image appears more or less continuous, as if it were made by applying a solution of a black dye. Examination at high magnification, however, reveals that it is made up of a lot of separate particles, which are so small and so close together that the eye normally cannot separate them. The photograph owes its particular discrete structure to the fact that the silver of the image is derived from small separate crystals of compounds of silver which make films, plates, and papers respond to light (Figure 6). Materials used for making negatives in the camera consist of silver bromide, usually containing a small percentage of silver iodide. The sensitive substance in printing papers is either silver bromide or chloride. The crystals range in size up to about $1/10,000$ in., depending on the kind of material. They are larger on the average in fast plates and films than they are in the slow materials.

The sensitive silver compounds are applied to the support or carrier in gelatin, in the form of an "emulsion." They actually are formed in the gelatin during the manufacture of the emulsion, by being precipitated from solutions of potassium bromide or chloride and silver nitrate. The emulsion is coated in a thin layer on film, glass, or paper and allowed to dry to a layer which is less than $1/1,000$ in. thick. The gelatin serves as a means of holding the silver compounds on the support and keeping the crystals separate from one another. It also plays a very important part in determining the sensitivity of the material to light and in influencing the course of development. The art of making emulsions involves the control of the crystals so that they are of a desired range of sizes, and the carrying out of the

process so that the product shall have the best photographic speed consistent with the ability to reproduce tones correctly.

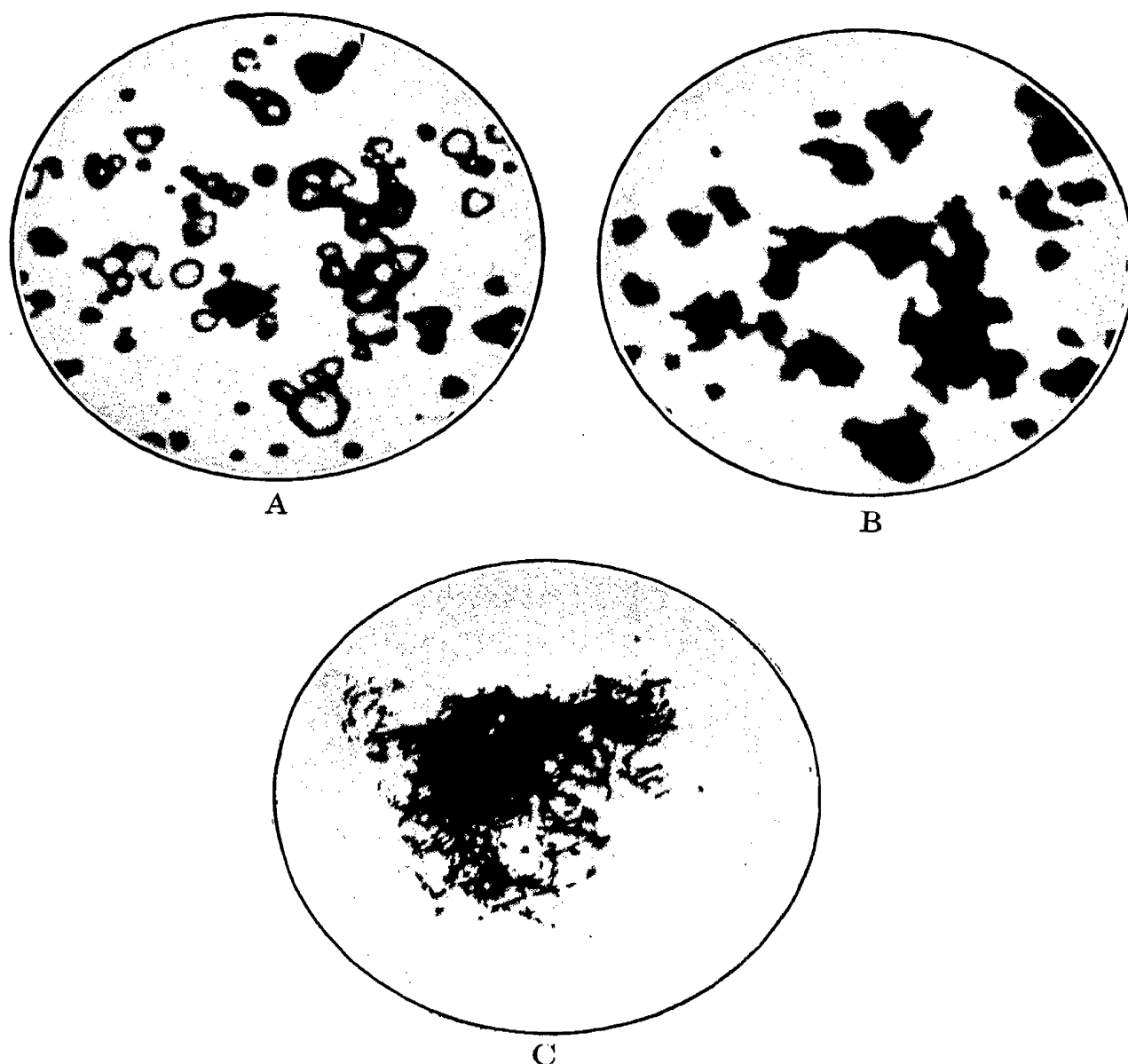


FIG. 6. Undeveloped and developed crystals in a photographic emulsion.
A. Photomicrograph of typical silver halide crystals in a fast emulsion.
B. The same crystals after exposure and development.
C. Electron micrograph of developed grain showing fibrillar structure revealed only at very high magnifications.

When a film or plate is exposed to light in a camera, some of the crystals are affected by the light. The actual number involved depends on the sensitivity of the material and on the exposure. The change which is produced by the action of light is not visible and is called the "latent image." It can be rendered

visible, however, by treatment in the solution known as a "developer." This converts the affected crystals to black metallic silver, but leaves unchanged those which were not acted on by light. It will be apparent that, if a photograph is made of a subject part of which is light and part dark, more silver particles will be formed where the bright areas of the image fall on the plate or film, whereas less will be formed in those parts corresponding to the darker portions.

Now, if there are a lot of black silver particles in a small area, this will appear blacker to the eye than those regions in which the particles are fewer. In other words, it will have a higher "density." The parts of the photograph corresponding to the bright sections of the subject will appear dark, and vice versa. The tones will be inverted, and the result is called a "negative." If the negative is copied onto another photographic material on paper or glass, the result is a "positive" print or transparency, whose tones are the reverse of those on the negative and so resemble those of the original subject.

In order to make a photographic negative stable to light, it is necessary to remove the silver compounds which are not converted to metallic silver by the developer. This is done by means of the "fixing bath" which dissolves silver iodide, bromide, and chloride, but leaves untouched the metallic silver of the image (see p. 41).

The theories of sensitivity, the latent image, development, and so on, and the characteristics of the emulsion which are related to them are dealt with very fully in textbooks of photography (in particular in the treatise by Mees³⁰). However, there are some properties of photographic materials and developers, a knowledge of which is very important for the practical photographer, for it will enable him to select his films, plates, and printing papers to the best advantage, and to expose and develop them to give the desired results. They are discussed here.

In ordinary black-and-white photography, the purpose of the photographer is to reproduce the relative tone values of the subject as faithfully as possible. These tones are due to different degrees of brightness in the thing photographed. Consider the case of a landscape in sunlight, with a few cumulus clouds in the sky. To the eye the brightest part will be the tops of the clouds.

The blue sky will appear somewhat less bright, the grass and leaves in the sunlight will be still darker, and the shadows under the trees will appear quite dark. In general, the brightest part of such a landscape will not be more than one hundred times as bright as the darkest part, and in many cases the range will be much less than this. In a good photograph of this subject practically the whole range of tone values must be recorded, and the half tones, or those intermediate between the brightest and darkest parts of the subject, must be rendered in the same relative values as the eye sees them.

There is one complicating element due to the fact that natural objects are usually colored. The eye distinguishes different tones not only because part of an object may be illuminated more than another, but also because it sees some colors as brighter than others. Now the photographic plate or film is likewise not equally responsive to all colors, and, in fact, the colors brightest to the eye may appear quite dark to the plate. In attempting to make a good black-and-white photograph of colored natural objects, therefore, it is necessary to use a plate or film which will respond to all colors of the objects, to modify the light which enters the camera in such a way that the effective response of the plate to different colors is the same as that of the eye, and to develop in such a way that the relative tone values are reproduced in the manner in which they are seen by the eye.⁸

Panchromatic plates and films respond to all the colors that can be seen, and they are therefore used in all normal photography when correct tone rendering is desired. To render their response to colors similar to that of the eye, it is necessary to modify the color of the light by means of color filters placed on the camera lens. In infrared photography there is naturally no question of tone values as the eye sees them, because the eye does not respond to infrared. The sole concern here is with what can be called photographic brightness. It is not possible to tell how things will look in an infrared photograph from a knowledge of their appearance to the eye. The infrared often reveals startling differences which are quite unsuspected from visual observation. It is actually in this property that the value of infrared photography lies.

The only essential difference between photographic materials for the infrared and for the visible spectrum lies in the region of the spectrum to which the former respond. The other characteristics are similar, and all can be measured. A knowledge of these properties of plates and films is very important for their successful use. Although photographs of great value are made by the thousand every day without any such knowledge on the part of the photographer, many cases occur where an understanding of the capabilities and limitations of the material would be of great benefit. This applies particularly to scientific photography and the interpretation of records. A rather complete discussion therefore will be given of the way in which plates and films respond to radiation and the manner in which the result may be controlled by proper handling.

For simplification, reference will be made mainly to films alone, but the statements also may be taken to apply to plates. The methods of determining the characteristics of plates, films, and papers embrace the science of "sensitometry."^{10, 17, 30} For convenience the subject will be divided under the following headings:

The Developed Photographic Image.

Density.

Relation of Density to Exposure.

Contrast, Gradient, Gamma.

Latitude.

Speed, Sensitivity.

Extent of Development.

Fog.

Color Sensitivity; the Effect of Wavelength.

Filter Factors.

Reciprocity Law Failure.

Intermittency Effect.

Graininess and Resolving Power.

Positive Materials.

THE DEVELOPED PHOTOGRAPHIC IMAGE. At the beginning of this chapter it was said that, when an exposed plate is developed, the silver bromide crystals affected by the exposure are converted to particles of metallic silver, while those not so changed are removed in the fixing bath. The photographic image thus con-

sists of large numbers of minute silver grains which give it its typical black appearance.

DENSITY. The presence of the developed silver grains gives a negative a certain "opacity" to light. The greater the number of grains in a particular area of the film, the more nearly opaque it is. It is customary in photographic parlance to refer to the "density" rather than the opacity of a photographic image, density being defined as the logarithm of the opacity. The expression "transparency" also is employed frequently. It is a measure of the proportion of light which the silver image will let through and is the reciprocal of the opacity. For instance, if the image lets through one tenth of the light which falls on it, it is said to have a transparency of 10 per cent, and an opacity of ten. The logarithm of ten is one, and so the image has a density of this value. If the image lets through one hundredth of the light which falls on it, the density is two, and so on.

The relation between transparency (T), opacity (O), and density (D) is shown in the following equations, where I represents the intensity of light falling on the photographic silver deposit, and I' is the intensity transmitted by it:

$$T = I'/I; \quad O = I/I'; \quad D = \log I/I' \quad \text{or} \quad -\log I'/I$$

The density of the silver deposit is approximately proportional to the amount of silver per unit area. It is measured in an instrument called a densitometer.

RELATION OF DENSITY TO EXPOSURE. As the exposure of a film is increased, the number of silver bromide crystals affected increases. This means that, on development of the film, the greater the exposure, the greater is the number of silver grains formed. In other words, the density of the image increases with exposure. If successive patches on a strip of film are exposed to increasing extents, and the strip is then developed, it will carry a series of steps of increasing density, the more exposed parts being denser than those less exposed. The relationship between density and exposure can be shown graphically in what is known as the "characteristic curve" of the film. In practice, the curve is traced by plotting density against the logarithm of exposure. A typical characteristic curve is shown in Figure 7. It is well to become acquainted with the significance of this curve, because it is the

most useful way of showing the properties of a film, and is commonly employed by the photographic technologist.^{10, 17, 30}

An examination of the curve will show that it consists essentially of three parts. The lower portion (*AB*) is concave upwards and constitutes the “toe” of the curve, corresponding to the low

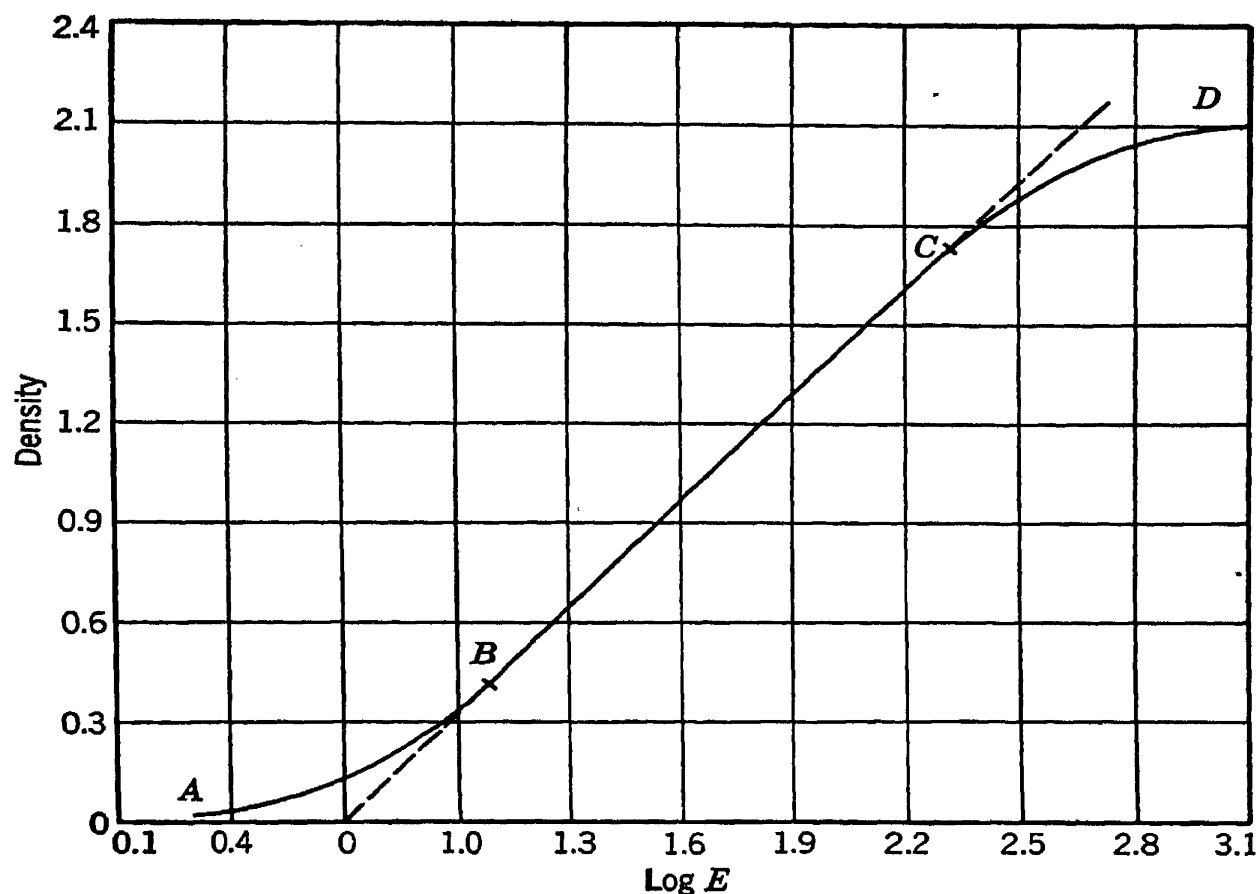


FIG. 7. Characteristic curve of a photographic emulsion.

exposures. The middle part (*BC*) is a straight line in a typical curve. The upper section (*CD*) is concave downwards and is determined by the highest exposures. It will be observed that a point is reached, *D*, where an increase in exposure produces no extra density. The value of density at which this occurs is known as the “maximum density.”

For many years it was believed that a perfect negative rendering of the subject could only be obtained if the brightness range of the subject were recorded within the limits of the straight line of the characteristic curve. This theory is now outdated as a result of considerations based on the judgment of print quality, and excellent photographs can be obtained if some of the negative

exposure is included in the toe of the curve. For a full discussion of the significance of the shape of the characteristic curve in the correct rendering of tones, the reader should refer to one of the textbooks on photography mentioned in the bibliography at the end of this chapter, especially that by Mees.³⁰

CONTRAST, GRADIENT, GAMMA. The contrast in a subject to be photographed is determined by the values of brightness of the lights and shades. These result in exposure differences in the camera. In a negative they are reproduced as densities, so that the "contrast" of the negative is determined by the density difference corresponding to the exposure difference. At every point on the characteristic curve there is a certain "gradient," or slope. In the toe of the curve, the gradient increases as the exposure increases. In the straight-line part, the gradient is constant with increase in exposure, whereas, in the upper region of the curve, increase in exposure gives decreasing gradient. The value of the gradient in the straight line may be expressed by the slope of the line. If the line is produced so that it cuts the axis of exposure at *O*, it makes a certain angle with the axis at that point. The tangent of this angle is the slope of the line and is usually known as "gamma" (γ). The value of gamma frequently is employed as a measure of the contrast of the plate. It will be apparent that, if gamma increased, the density difference corresponding to a particular exposure difference would also increase.

EXPOSURE LATITUDE. It is desirable that the range of brightnesses of a subject photographed should be able to be recorded within the useful limits of the characteristic curve. The useful limits, which are associated with the minimum useful gradients in the upper (shoulder) and lower (toe) regions of the characteristic curve, determine the exposure latitude of a film. The lower limit, which is indicated at *A* in Figure 7 normally occurs at a point on the curve where the gradient is slightly less than three tenths of the slope of the straight-line portion of the curve, or the region between points *B* and *C* in Figure 7. The upper limit, which is shown at point *D* in Figure 7, occurs at a gradient which is slightly higher than that at the lower limit.

Fortunately most negative materials will record a greater brightness scale than is associated with most scenes. It is rather

the printing material which determines the brightness range of a scene which can be reproduced.

SPEED, SENSITIVITY. The property of a film which determines the readiness with which it responds to light is called its "speed" or "sensitivity." A film which permits a photograph to be taken with a short exposure or a little light has a higher speed than one which requires a longer exposure or more light for the same result. Many methods for the determination and specification of speed have been suggested, but there is no international agreement on a single suitable system. The American and German Standards Associations each agreed on a national system, although they did not agree with each other.

It seems reasonable to define speed in terms of the least exposure which can be given to obtain an acceptable result. In the case of ordinary photography the desired result is a good print. However, in other applications an entirely different criterion may be necessary. For example, in spectrographic work, it may be necessary merely to see a sufficient trace of a spectral line to be able to measure its position. In copying line drawings, speed is determined by the exposure which will give a satisfactory high-density contrast between the line and its background under the most favorable conditions of development.

Of the several methods which have been used for the determination and expression of speed of films for general photography, most are now only of historical interest, and only brief mention will be made of them.^{5, 10, 30, 32, 35} The Warnerke, Eder-Hecht, and Scheiner systems depended on the determination of the exposure which would give a just perceptible density. In the Hurter and Driffeld (H. and D.) system, long popular in England, the speed was defined by $34/i$ where i is the "inertia," and is the exposure corresponding to the point where the prolongation of the straight-line part of the characteristic curve meets the exposure axis. Variations of the inertia system were used in England (the Watkins and Wynne systems) and in the United States, where 34 was replaced by 10 or 2 in the H. and D. fraction.

In Germany, the DIN system was adopted as the national standard in 1934.^{15, 16} In it the speed is derived from the exposure required to produce a density of 0.1 above the fog level,

the development being carried to such an extent as to give the highest speed figure.

In the United States, it has for many years been the opinion among photographic research workers that, ideally, speed should be determined on the basis of an exposure required to give a particular slope of the characteristic curve, rather than a particular density. It is reasonably argued that, since we are concerned with the reproduction of brightness differences as density differences, we should use a gradient rather than a density criterion. Moreover, it is believed that the exposure should be the minimum which will give a negative from which a print of excellent quality can be made. A very exhaustive study of the subject from these points of view was made by Jones and his coworkers, starting with a statistical psychophysical investigation, and then deriving a practical method.^{4, 19-21, 23, 24} As a result, the so-called "fractional-gradient" method was evolved, and in 1943 it was adopted by the American Standards Association as the American standard method for speed determination for certain types of film for general photography outdoors.¹

In the American standard method, the criterion of speed is the exposure, E , corresponding to the point on the characteristic curve where the gradient is equal to three-tenths of the average gradient over a log-exposure range of 1.50. The method is illustrated in Figure 8.

This relationship gives the so-called "ASA speed." A practical adaptation of the ASA speed is the "speed number" or "exposure index," which refers to the recommended exposure for normal photographic practice which will yield the highest percentage of excellent pictures. The ASA speed is represented by $1/E$, and the value is written with a zero in front, that is, if $1/E$ is 200, the speed is written as ASA 0200, and the speed number or exposure index is one quarter of the ASA speed. These numbers correspond to those commonly used in some popular exposure meters and exposure computers. In the case of other classes of films than those provided for in the standard, another factor than one fourth may be used.

In all systems of speed measurement, a strip of plate or film is exposed in a "sensitometer" to give a series of steps of increasing exposures, the values of which are known. A standard re-

peatable source of light is used, and the exposure modulation is obtained in a variety of ways. If the steps increase only in the time of exposure, the intensity of the light on the test strip being held constant, the method is referred to as "time scale." It is usually effected by passing a rotating disk or "sector wheel," or a falling plate, carrying a number of slots of different lengths, be-

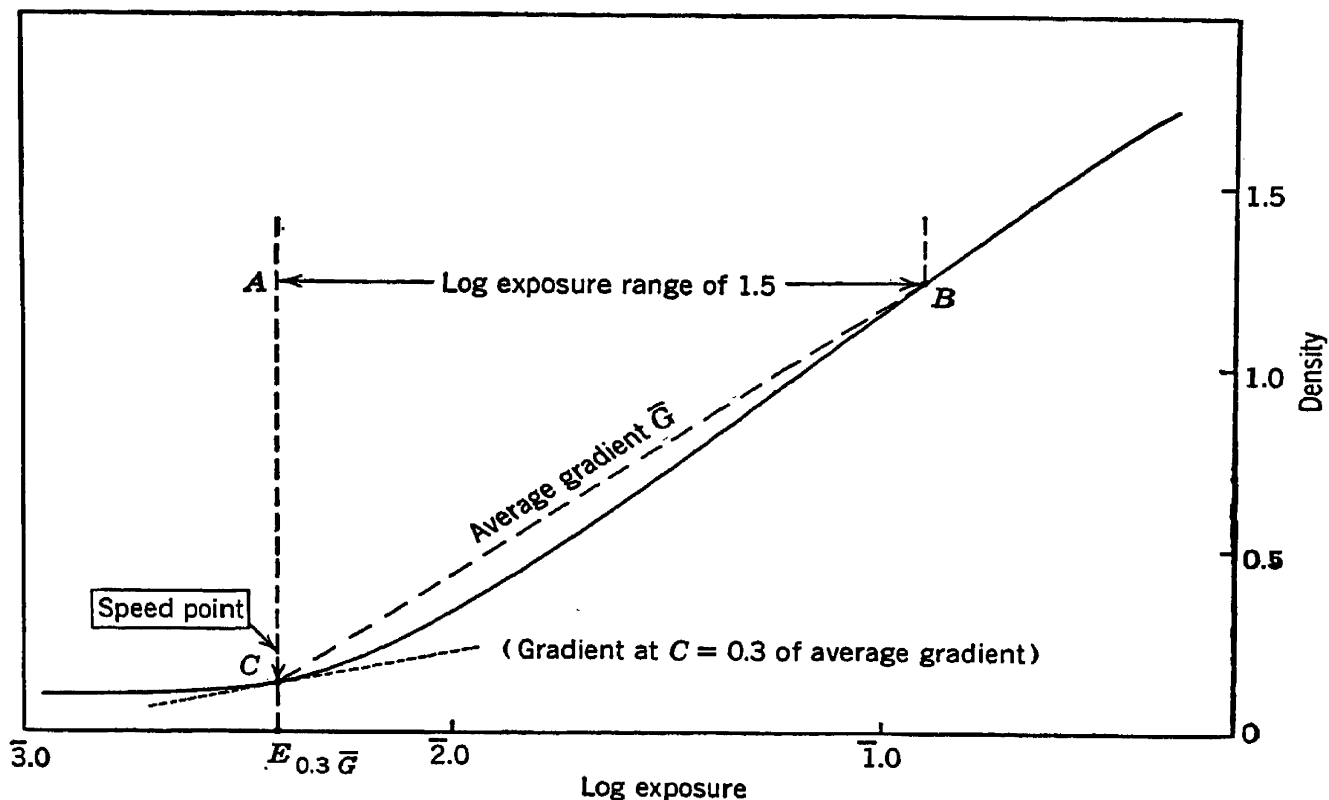


FIG. 8. Estimation of speed by fractional-gradient method.

Speed is based on the exposure corresponding to the point C , at which the gradient of the curve is $\frac{3}{10}$ of the slope of the line CB .

tween the light and the plate under test. If the time of exposure is held constant for all steps and the intensity varied, the system is called "intensity scale." The sensitometer in this case usually is a "step wedge" or "step tablet," consisting of a series of areas of increasing density. The exposure in each step is defined in terms of the intensity in visual candle power of light of specified quality, at a distance of 1 m, multiplied by the time of exposure in seconds.

In 1928 the International Congress of Photography agreed to specify the photographic unit of intensity as *one visual candle-power of light of approximately sunlight quality*.¹⁴ This was

defined as obtained by the use of a tungsten-filament lamp operated under specified conditions and screened with a filter of specified composition, and corresponding in spectral quality to a light source of approximately 5,400° K.

The standard lamp-and-filter combination which gives light closely approximating mean noon sunlight in quality, of course, refers only to visible light. Infrared-sensitive materials respond to violet and blue in the visible, but their infrared sensitivity is in the invisible region beyond 7,000 Å. In the infrared the international filter absorbs much too strongly. At 8,000 Å practically nothing is transmitted by it, so that exposures made through it do not compare with those made with sunlight. In order to determine the sensitivity of materials in the infrared region, it is desirable to use a combination of a lamp and filter which gives a spectral distribution beyond 7,000 Å equivalent to that of sunlight. This can be done by using a tungsten-filament lamp combined with a particular type of heat-absorbing glass and a filter which will absorb the violet and blue. For measuring the speed of infrared materials to white light the international standard lamp and filter are used, but for determining the speed in the infrared the special combination must be employed.

When speeds are given to infrared films in the old conventional units (H. and D., and the like), they are usually obtained in the following manner: A film of known speed and sensitive to white light is exposed to a subject to give a good negative, and the exposure is noted. The exposure required to give an equally good negative by infrared on the infrared film is also found, and the ratio between the two exposures is calculated. The figure obtained is divided into the known white-light speed of the former film, and the result is taken as the speed of the infrared material.

EXTENT OF DEVELOPMENT. The density of an exposed negative increases during development, eventually reaching a maximum value. If the negative has different exposures at different points, the densities corresponding to these increase with time of development in such a way that their ratios remain constant, provided they are on the straight-line part of the characteristic curve. Expressed in other words, as development is continued each density increases to the same proportional extent. For example, if a doubling of the development time adds 50 per cent to the

density of the shadows of the image it will also increase the density of the half tones and the highlights by 50 per cent. This results in an increase in the contrast between the highlights and shadows and is evident in the characteristic curve as an increase in its slope.

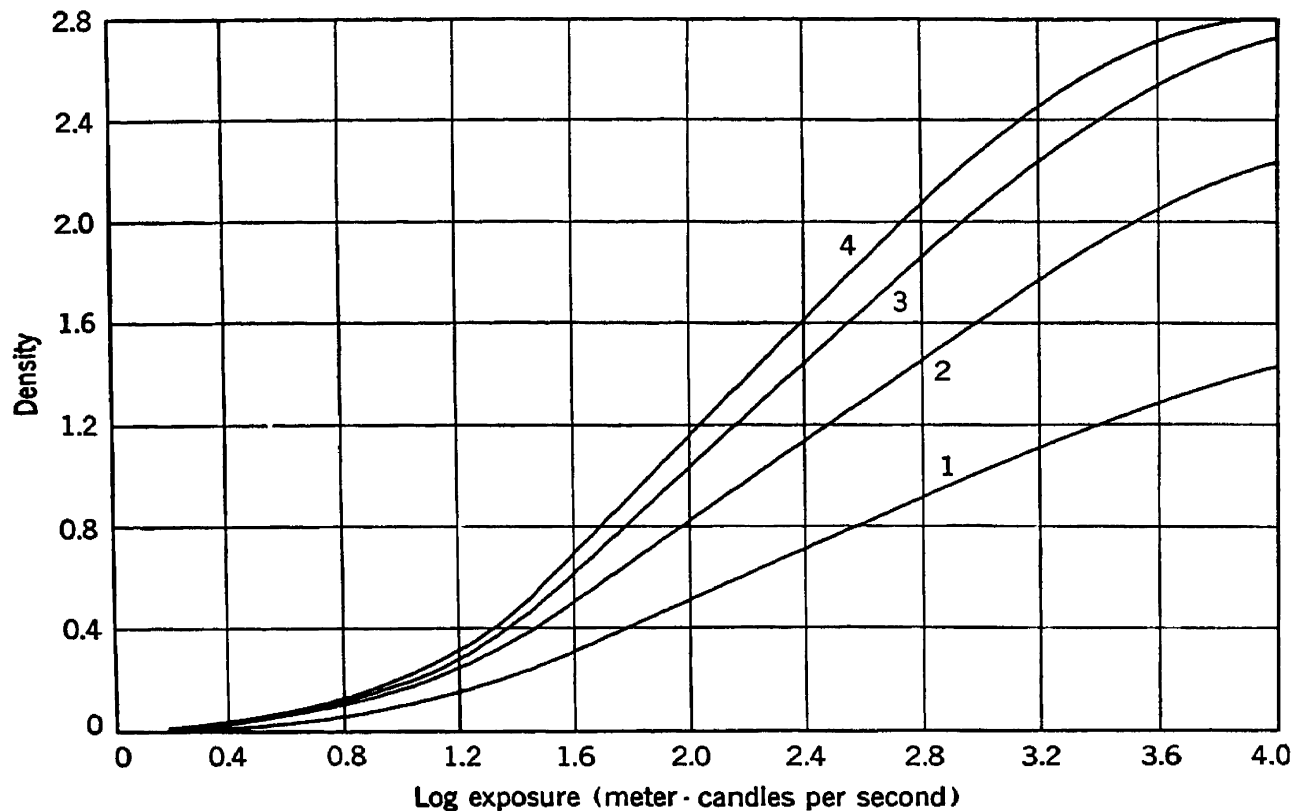


FIG. 9. Characteristic curves of a negative film showing the effect of increasing the time of development.

The development times increased in the order 1, 2, 3, 4.

The curves in Figure 9 show the manner in which the contrast and gamma of a negative increase with time of development. If the development is sufficiently prolonged, a stage will be reached at which no further increase of contrast is obtained with longer development. In fact, lengthened development will then tend to decrease rather than to increase gamma, since it will give rise to fog (see p. 58), which has a greater effect on the lower densities than on the higher ones. The maximum contrast or highest gamma obtainable with a particular photographic material is termed "gamma infinity" (γ_{∞}). If the gamma is plotted in a graph against the time of development, the curve has the exponential shape as shown in Figure 10. Such a curve is called

the "rate-of-development curve," or, simply, the "time-gamma curve."

The time-gamma curve describes the change in the rate of development with time. It increases rapidly at first and then more slowly until it reaches the limit at γ_{∞} . The relation can be

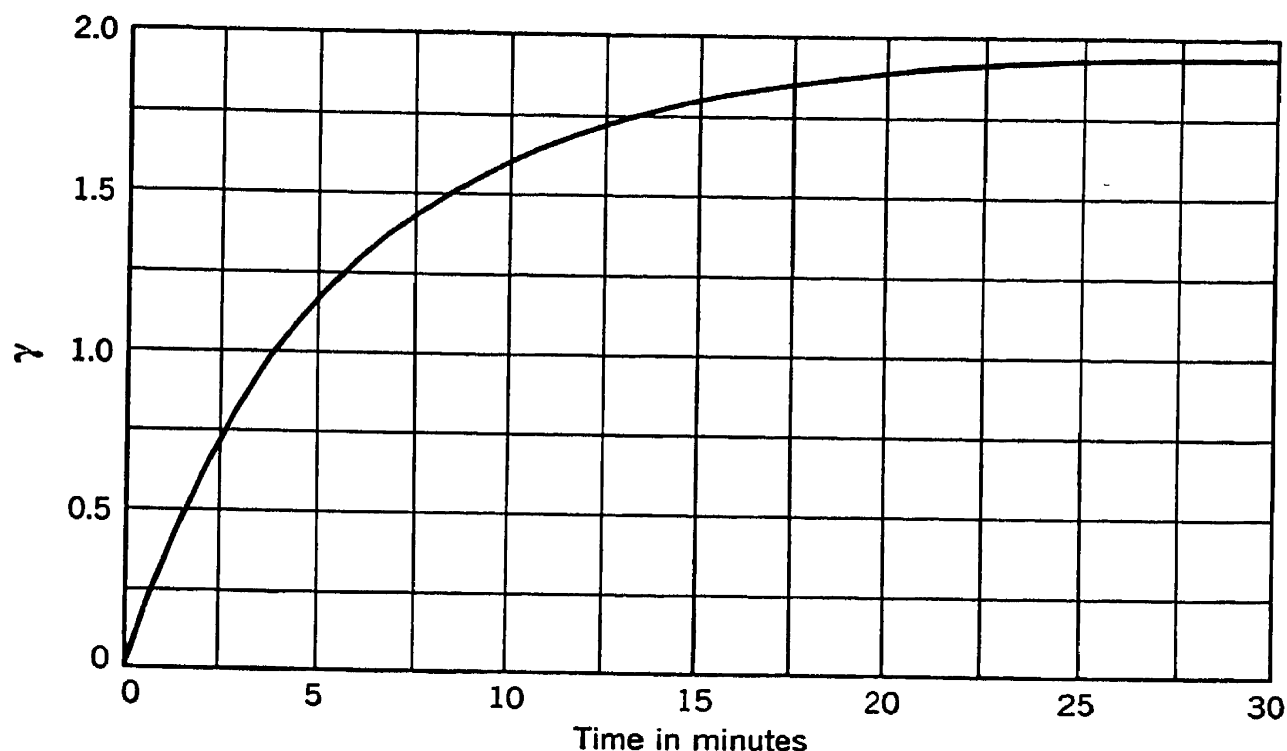


FIG. 10. Curve showing the rate of development of a photographic emulsion.

The curve is obtained by plotting gamma against time of development.

represented approximately by the equation of the rate of a chemical reaction of the first order,

$$\gamma = \gamma_{\infty}(1 - e^{-kt})$$

where γ and γ_{∞} have the significance already mentioned, t is the time the development has progressed to give the value of γ under consideration, k is the velocity constant of development which is dependent on the nature and temperature of the developer used, and e is the base of natural logarithms.

The limit of contrast (γ_{∞}) obtainable depends not only on the developer but also on the photographic material. Plates and films of very high speed, and particularly those used for portraiture, have a rather low gamma infinity. Those of medium

speed, used for commercial photography and landscape work, have higher values. The greatest contrast is obtainable with certain slow emulsions made for photoengraving work, with which values of gamma up to six or more can be produced. In general, the contrast obtainable with commercial plates and films increases as the material is slower. This rule is not without exceptions, although it can be assumed in most cases that if high contrast is desired the plate will be slow.

Fog. In the ideal photographic material, no silver bromide grains would develop if there had been no exposure to light. In practice, however, a certain amount of density is usually produced in these circumstances. It is known as "fog," if it is not deliberately due to exposure. Fog may originate in several ways. It may be inherent in the emulsion and arise from grains made developable during manufacture. Fog due to this cause is usually encountered more often in the case of very fast materials than with slow ones. Another form of inherent fog may arise if the films are kept for a long time, particularly at higher temperatures. If extraneous light to which the film is sensitive falls on it during manufacture or handling, it may give rise to light fog. Another common kind of fog arises in development. It can be due to the presence of chemical fogging agents in the developer and to oxidation of the developer by the oxygen of the air. Manufacturers of photographic materials strive to keep inherent fog as low as possible. The density due to fog increases with the extent of development, and the amount of fog present is greater in the lower densities than in the higher.

COLOR SENSITIVITY; THE EFFECT OF WAVELENGTH. The simplest silver bromide films are sensitive only to the ultraviolet and to violet and blue light. They are treated with certain dyes to make them respond to the green, red, and infrared. The methods of dye sensitizing are considered in full in Chapter V. It will suffice here to refer to certain effects of this addition of dyes. The chief function of sensitizing dyes is to make the emulsion respond in spectral regions to which it is not normally sensitive. It is very important that it record all visible wavelengths if it is to be used to give faithful tone reproduction of an object, and that it be as sensitive as possible in the infrared if it is to be used for photography in this region. The effective response of a film or plate to

different spectral regions obviously depends on the characteristics of the source of radiation used. If there is no infrared, for instance, no amount of infrared sensitivity will permit an infrared photograph to be made. If there is a lot of energy in the red as compared with the blue, this will tend to emphasize the response of the plate in the red and hold it back in the blue.

In measuring the spectral sensitivity of a film, it is customary to trace a curve showing its response to light of a particular spectral quality, such as sunlight or a tungsten-filament lamp, or to an ideal source in which there are equal amounts of energy at all wavelengths. All practical light sources have characteristic energy distributions which are described in Chapter VII. The spectral response to a certain source is very conveniently shown by making so-called "wedge spectrograms." The plate or film under test is put in a spectrograph, over the slit of which is a grey optical wedge which is completely transparent at one end and which increases in density along its length so that it transmits, say, only 1/10,000 of the light at the dense end. Without the wedge over the slit, the photograph of the spectrum obtained is a band of uniform height extending over the range of wavelengths to which the material is sensitive, and varying in density according to the sensitivity. With the wedge in position, however, the photograph obtained will vary in height according to the response of the plate to each particular wavelength.

A diagram of the optical system of a wedge spectrograph is shown in Figure 11. Light from a suitable source is dispersed by means of a diffraction grating, and the spectrum which is produced is allowed to fall directly on the photographic material. The instrument shown is designed for use in the visible spectrum. It can be modified for the infrared in such a manner that the collimator lens, slit, condenser lens, and light source may be rotated about a horizontal axis through the center of the ruled surface of the grating, while the camera, camera lens, and grating remain fixed. If the collimator and camera lenses are sufficiently achromatic over both the visible and near-infrared regions, refocusing and tilting of the platcholder will be unnecessary. The wedge spectrograph illustrated in the figure was designed by Mecs, and is sold by Adam Hilger, Ltd., who also have

available another model specially designed for use in the infrared from 6,200 to 11,000 Å.

Typical wedge spectrograms obtained in this way on ordinary, orthochromatic, panchromatic, and infrared films are shown in Figure 12. A scale of wavelengths is impressed on the spectrogram, and each horizontal line corresponds to an intensity decrease of one tenth as compared with the intensity at the line below it. Owing to the absorption of the wedge and the glass

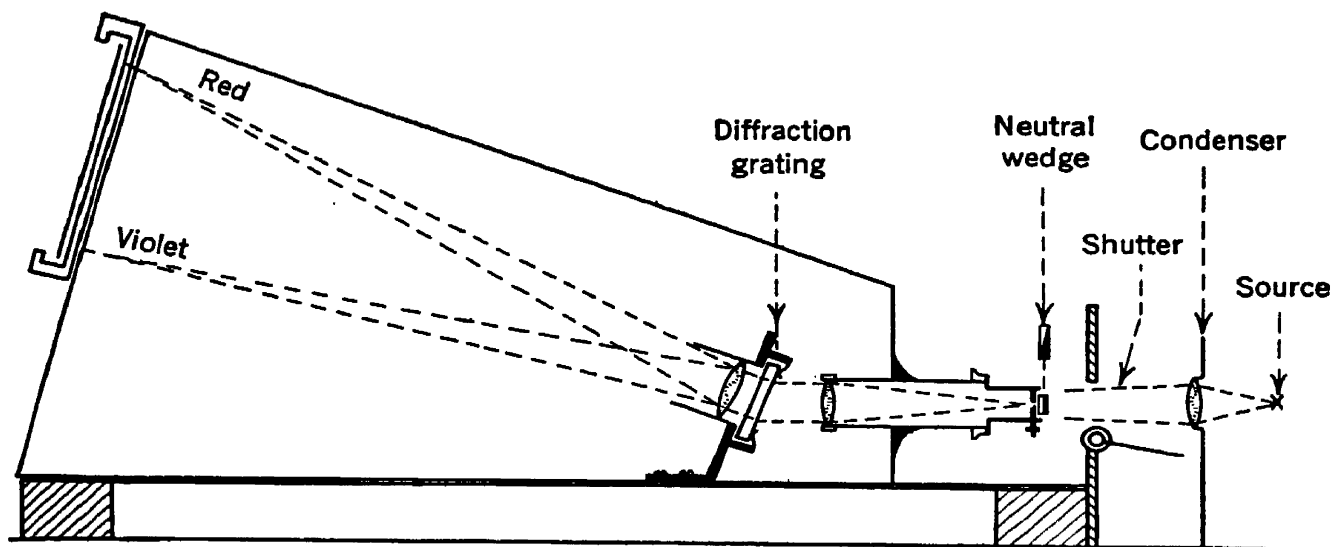


FIG. 11. Diagram of wedge spectrograph.

in the spectrograph, the response to the ultraviolet is not shown.

In order to show the spectral sensitivity independently of the characteristics of the light source, so-called "equal-energy spectral-sensitivity curves" are made. Narrow spectral regions are isolated by means of a spectroscope, and characteristic curves of the material are made to a series of these regions spread through the spectrum. From these curves, the sensitivity values for equal amounts of energy at each wavelength are obtained and plotted in a curve against the wavelengths. Curves obtained in this way are shown in Figure 20 (pp. 88-90).

Dye sensitizing not only affects the sensitivity of a material to particular wavelengths, but also has a pronounced influence on other characteristics, the chief of which is the contrast. In general, the contrast is lowest for the shortest wavelengths and usually shows a very marked increase in the infrared.

FILTER FACTORS. In order to modify the spectral quality of the exposing light, it is common practice to use light filters (see

Chapters II and XVI). These are sheets of gelatin or glass which are dyed so as to transmit the desired wavelengths and absorb the others. If light is absorbed in the region of the spectrum to which a film responds, it is obvious that an increase in exposure will be necessary to obtain a negative equal in density to that

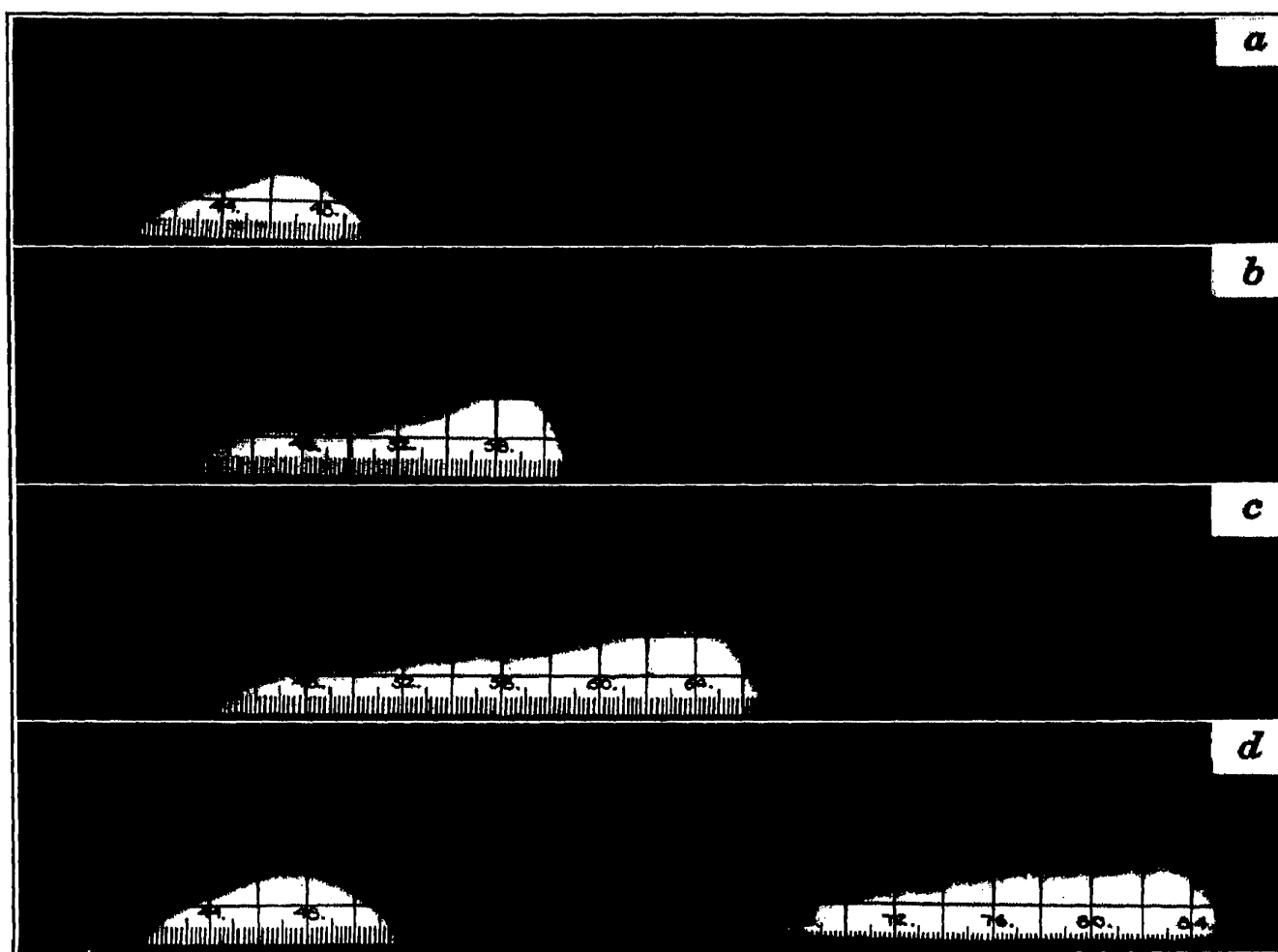


FIG. 12. Wedge spectrograms of typical photographic materials: *a*, ordinary; *b*, orthochromatic; *c*, panchromatic; *d*, infrared.

given by unfiltered light. The number by which it is necessary to multiply the exposure to obtain this equality is called the “filter factor” of the filter. The value of this factor depends on the nature of the filter, the sensitivity of the emulsion, and the spectral quality of the source of light.⁸ So-called filter factors are sometimes published for infrared materials. In practice, however, infrared films scarcely ever are exposed without a filter, so that a filter factor has little value when applied to a filter for use with them.

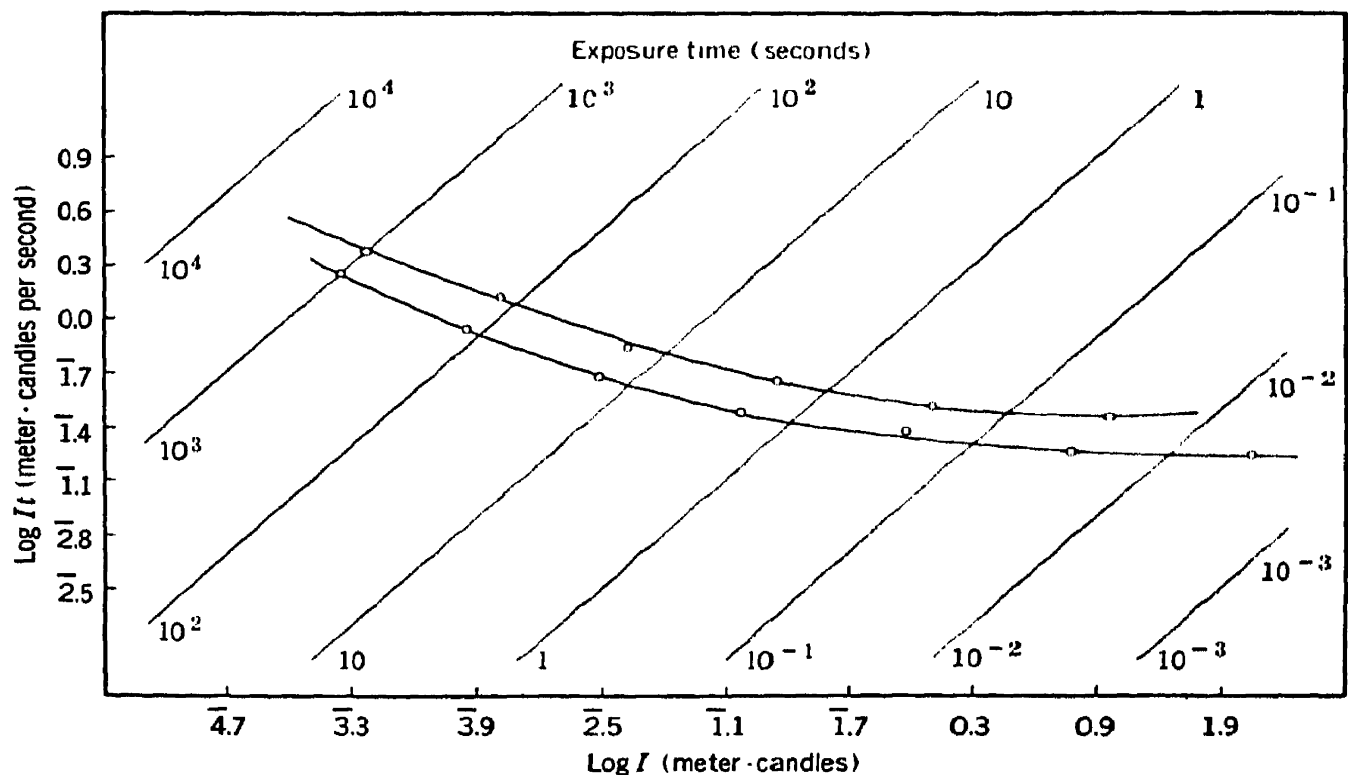
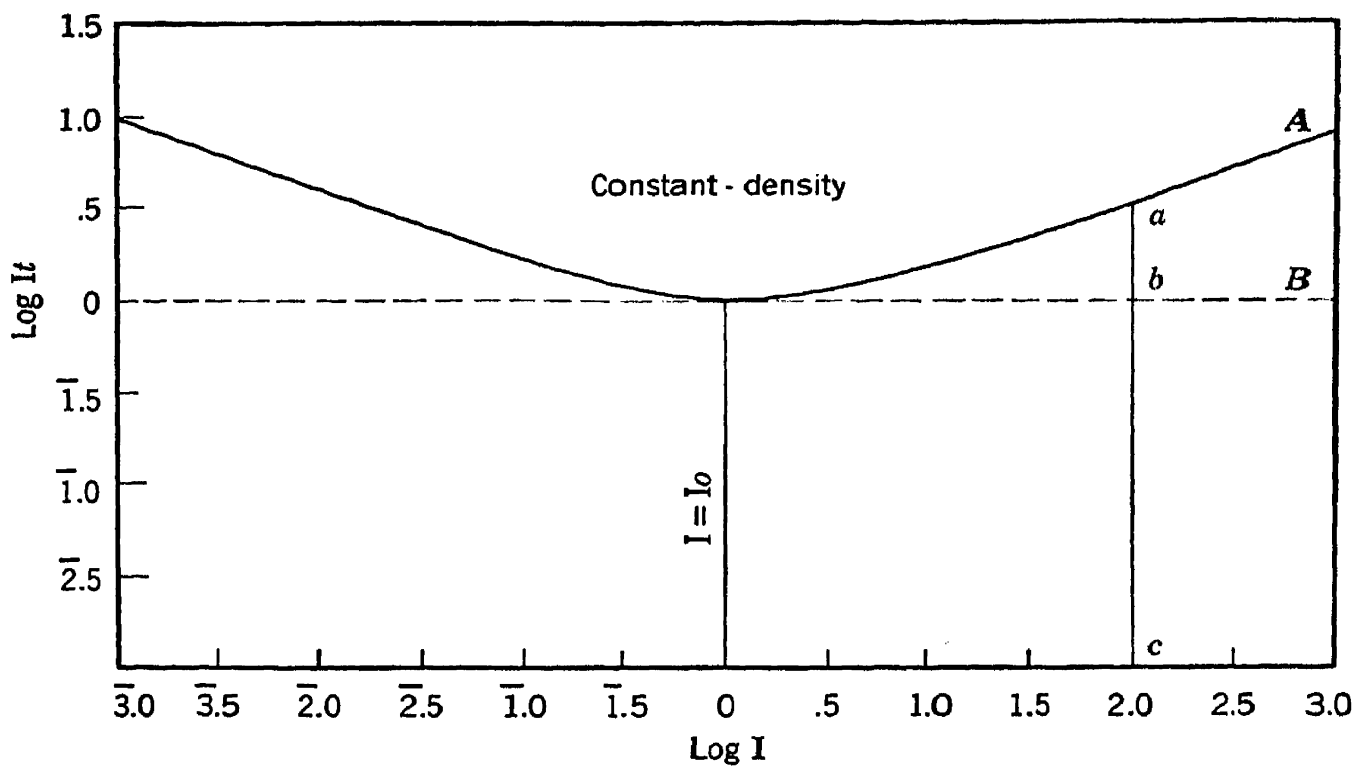
RECIPROCITY LAW FAILURE. The sensitivity of a photographic material depends on the intensity of the radiation used in making the exposure, and all materials show to some extent the phenomenon known as the "failure of the reciprocity law." The reciprocity law, enunciated by Bunsen and Roscoe for photochemical reactions, stated that the result of such a reaction depended solely on the total amount of energy employed, that is, on the product of intensity, I , of the light multiplied by the time, t , of its action. Provided the product of these remained constant, the effect produced was constant. This is found not to be true in the case of photographic materials. The density obtained by a certain exposure, E , is not independent of the absolute values of I and t where $E = It$. With the long exposures at low-intensity levels met in astronomy, for instance, the failure may assume large proportions and is a very important factor in determining the choice of materials, especially in photographic photometry.

Many workers have studied the failure of the reciprocity law, and many so-called laws have been deduced to define the relationship between the magnitude of the response and the values of the time and intensity factors of exposure. One which has received widespread acceptance is known as the Schwarzschild law, after the German astronomer who enunciated it. According to this law, the effect of a photographic exposure E can be expressed approximately in terms of the equation,

$$E = It^p$$

where I is the intensity, t is the time of exposure, and p is a constant. The matter was investigated by Kron, who found an equation of the catenary type to hold, the value of p not being constant but varying continuously with the level of intensity, and this result has been confirmed by Huse, Jones, Hall, Webb and others.^{26, 30, 36-39} Schwarzschild's law holds only over a limited range of low intensity.

A typical reciprocity curve is shown in Figure 13. The curve *A* shows the relation between $\log I$ and $\log It$ for constant values of image density. Curve *B* represents the condition which would exist if there were no failure of the reciprocity law. It will be observed that there is an intensity value to which there corresponds a minimum value of exposure necessary to produce a



The upper curve is for Kodak Infrared Sheet Film, and the lower is for Eastman Infrared Aero Film Type 2 (of 1943).

specified density. This value of intensity is known as the "optimal density." It is evident that for intensities above or below the optimal, a higher exposure (It) is required to produce the particular density.

The reciprocity curves for Kodak Infrared Sheet Film and Eastman Infrared Aero Film are shown in Figure 14. Their spectral sensitivity resembles that shown as D in Figure 11. The diagonal lines in Figure 14 represent equal exposure times and

TABLE VI

FRACTIONAL GRADIENT SPEEDS AT DIFFERENT LEVELS OF INTENSITY

<i>Film</i>	<i>Camera Level, $I = 2$ M-C</i>	<i>Spectroscopic Level, $I = 0.1$ M-C</i>	<i>Astronomical Level, $I = 0.0001$ M-C</i>
Tri-X Panchromatic	640	520	82
Super-XX Panchromatic	250	180	23
Plus-X Panchromatic	125	110	16
Commercial	25	22	5
Super Speed Ortho	100	155	62
Infrared Sheet	25	15	1.3

M-C = meter-candle.

facilitate the calculation of exposures in terms of time values. Table VI is included to give some idea of the change in speed of a number of Kodak and Eastman photographic materials when the intensity level of exposure is changed. The intensities are in meter-candles and correspond to levels which might be encountered in the camera, the spectrograph, and in astronomical work.

It will be seen that the relative speeds of photographic materials may change considerably according to the intensity level at which the exposure is made. The values of speed given in the table are in terms of the fractional-gradient method (see p. 54).

The reciprocity relationship depends on a variety of factors other than the nature of the emulsion. These include the type of sensitizing, the character and extent of development, bathing the emulsion in dilute solutions of silver salts, and hypersensitizing with ammonia. The addition of silver ions and hypersensitizing tend to decrease the reciprocity-law failure at low intensities.

It has been considered worth while to go into this matter in some detail because results due to the failure of this law fre-

quently are encountered in photographic practice, particularly when the photographs are to be used for measurement, as in photographic photometry. For a fuller survey, the reader is referred to the publications mentioned in the bibliography, particularly the article by Jones¹⁷ and the book by Mees.³⁰

INTERMITTENCY EFFECT. If a photographic material is exposed for a certain time, t , in a series of short flashes which add up to t , the photographic effect produced usually will be different from that obtained if the exposure is made continuously for the time t . The density due to the intermittent flashes may be greater than, equal to, or less than that due to the continuous exposure. This is known as the "intermittency effect."^{37, 38} This effect is of considerable importance, because in some kinds of work, such as absorption spectrophotometry, the exposure is intermittent, owing to the use of a rapidly rotating exposure disk. If the frequency of flashes is high enough, say, exceeding 100 flashes per second for a one-second exposure, the intermittent exposure produces the same effect as a continuous exposure of the same total time.

These facts indicate clearly that great care must be exercised in planning the method of exposure when photographic materials are used for the measurement of radiant energy.

GRAININESS AND RESOLVING POWER. In addition to their sensitometric characteristics, photographic materials differ in two important properties—graininess and resolving power. In general, if a developed film is examined under low magnification, the image will be found to possess a granularity which is far coarser than the individual silver grains themselves. This granularity depends on a number of factors.³⁰ It is primarily dependent on the nature of the emulsion, being, in general, more noticeable with fast emulsions than with slow. It also depends markedly on the nature of the developer, and increases with the time of development or the contrast, and with the density of the image, reaching a maximum at a density of 0.6–0.8. In prints, graininess increases as the density of the negative increases. The definition of the image given by the camera lens also plays an important part; if it is poor, graininess is diminished, but so also is the image quality. Graininess limits the degree of enlargement which can be attained without disturbing the uniform appearance of the

image and breaking up fine detail. It can be reduced by avoiding the causes mentioned above, but particularly by selecting emulsions which tend of themselves to give low graininess, developing to a low gamma, and choosing a developer which keeps the effect to a minimum. Many so-called "fine-grain developers" have been proposed. In addition to their effect on the grain, they all have the characteristic of reducing the effective speed of the emulsion. There is no developer known which will reduce the tendency to graininess without at the same time causing loss of speed. In selecting a fine-grain developer, the photographer will usually be guided by the desired reduction in grain considered in relation to the permissible loss of speed. It might frequently be desirable to start with a slower film or plate in which the graininess is inherently lower and use a normal developer. Another factor which must be considered is the nature of the developer; solutions containing paraphenylenediamine as the active developing agent tend to cause marked dermatitis in many users.

The resolving power of an emulsion is defined by its ability to distinguish fine detail in the image.³⁰ It is usually expressed as the number of lines per millimeter which can just be separately distinguished on the plate. It is dependent on the turbidity of the emulsion, its contrast, the spectral quality of the exposing radiation, the image density, and the contrast of the optical image photographed. In general, the resolving power increases as the emulsions are slower and of higher contrast. For instance, the fast negative emulsions usually have a resolving power of 40 or 50 lines per millimeter, positive types of emulsion may resolve 80 to 100 lines, and the very slow materials of high contrast used in photoengraving may separate 150 to 200 lines per millimeter. Special emulsions with a resolving power of more than 1,000 lines per millimeter have been made for the production of reticles. The resolving powers for a number of infrared films for test-object contrasts of 1,000:1 and 30:1 and normal development are shown in Table VII.

OTHER PROPERTIES. In addition to the effects mentioned, there are several other influences which must be borne in mind if the photographic plate is to be used for quantitative measurement of radiation:

1. The latent image may be subject to a growth or decay between exposure and development. The magnitude of these effects cannot be predetermined with any degree of precision, and they depend on a variety of factors which include the nature of the emulsion; the temperature, humidity and other conditions at the time of exposure; the conditions of keeping between exposure and development; and the kind of development.

2. The response to light depends to some extent on the temperature and humidity at the time of exposure. Raising the

TABLE VII
RESOLVING POWER OF INFRARED FILMS

<i>Film</i>	<i>Gamma</i>	<i>Density for Maximum Resolving Power</i>	<i>Resolving Power</i>	
			1,000:1	30:1
Kodak Infrared Sheet Film	1.4	1.4	50+	50
Kodak Infrared Film (Miniature and Roll)	1.4	1.2	55	50-55
Eastman Infrared Negative Film (35 mm)	0.9	0.9	60+	60
Kodak Aerographic Infrared Film	2.0	1.7	45+	45+

temperature above normal may produce a slight speed increase, whereas lowering it to well below 0° C may reduce the speed to half. This is a matter of importance in high-altitude aerial photography, where very low temperatures are encountered.

3. There may be variations in effective sensitivity of the material from one point to another, due to inequalities in emulsion thickness, differences in the actual sensitivity of the emulsion from point to point, and variations in the rate of development. For a fuller consideration of these and other effects, and the conditions to be observed in using the plate or film for radiation measurements, the reader is referred to the excellent article by Jones.¹⁸

POSITIVE MATERIALS. Brief mention should be made of the characteristics of paper printing materials, since the photographer usually makes prints from his negatives. The characteristic of a print differs from that of a negative, primarily because

it is made on an opaque paper support and is viewed by reflected light. In the case of a transparent negative, an increase in the silver deposit will always diminish the transmitted light, or in-

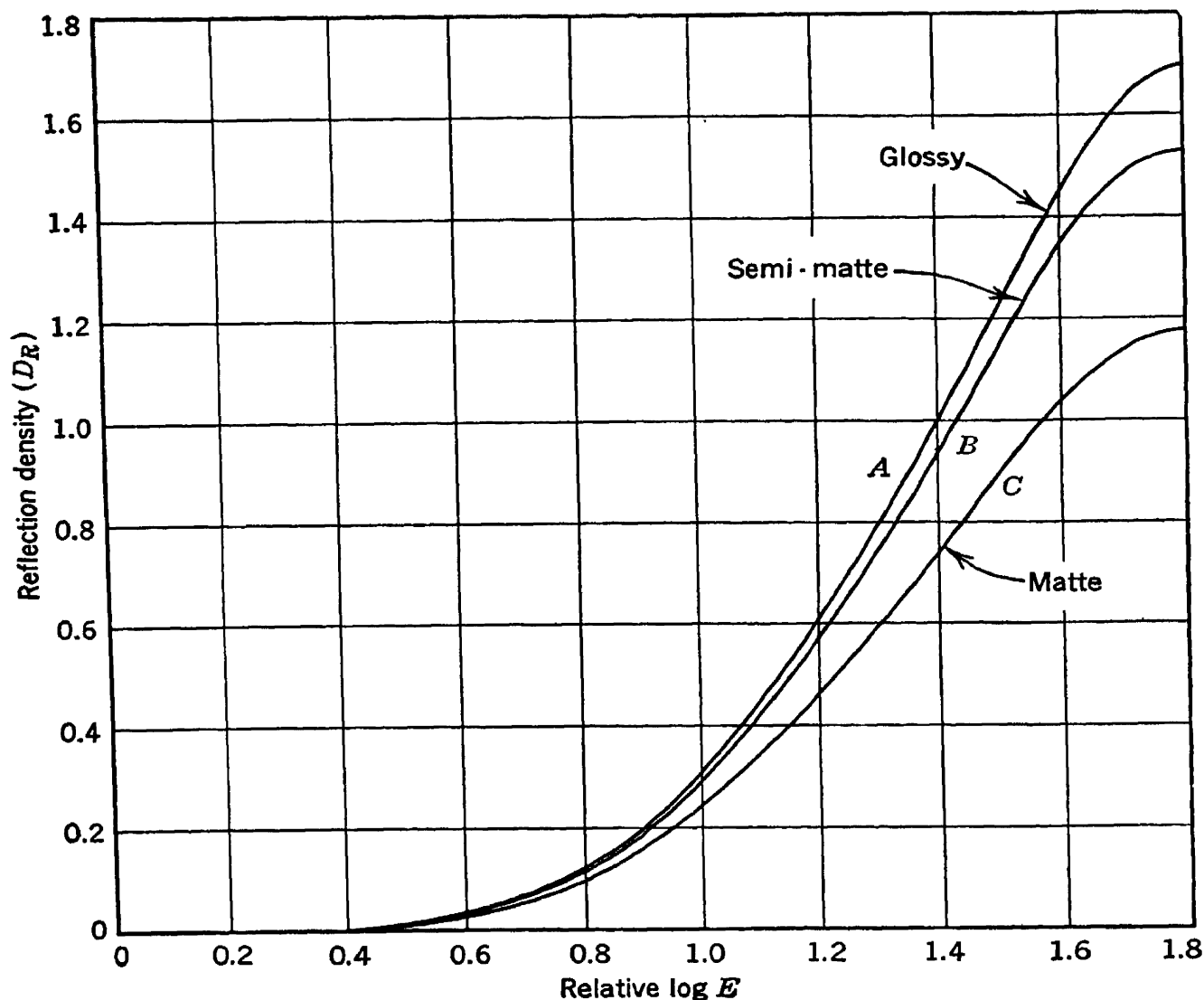


FIG. 15. Characteristic curve of photographic printing paper.

A, B, and C are for the same kind of emulsion, but they have a glossy, semimatte, and matte surface, respectively.

crease the density, without limit. This does not apply to prints, where an increase in the silver deposit will not produce a decrease in the light reflected after a certain deposit is reached. The reason for this is that some light is reflected by the surfaces of the silver itself and of the gelatin overlying the silver image and paper. The image density results from the silver stopping the light in two stages: as it passes through it on its way to the paper, and as it passes back through it after reflection by the paper.

Increase in the silver deposit affects this, but is without influence on the light reflected by the surfaces of the silver and gelatin. There is, therefore, always a certain amount of light reflected by the blackest parts of the print, and this places a limit on the density of the print which can be obtained.

Characteristic curves are obtained for papers in the same manner as for films²² by plotting density against the logarithm of the exposure, although for papers "reflection densities" are used. Typical curves are shown in Figure 15, in which *A*, *B*, and *C* relate to papers having glossy, semimatte, and matte finishes. It will be noted that the maximum density decreases as the gloss becomes less and the surface becomes more diffusing. Curves for different contrast grades of paper show correspondingly different slopes. In the chloride papers used for contact printing there is little change of contrast with time of development, whereas in enlarging papers the contrast usually increases with the time of development.

The contrast of a printing paper is not easy to define. It involves the maximum black, the slope characteristics of the curve (there is very little straight line)—in particular the maximum slope and the total scale, which is the range of light intensities that can be reproduced by the paper as areas differing perceptibly in density.

In choosing a paper for printing from a particular negative, it is clear that, if all gradations on the negative are to be reproduced as gradations in the print, the scale of the paper must be at least as great as the difference between the maximum and minimum densities of the negative. It is actually found that the useful maximum density of a printing paper is generally appreciably below the available maximum density, while the useful minimum density is about zero. It is preferable to use gradients rather than densities, and it appears that the limits of the useful portions of the curve of a printing paper are at fractional gradients of about 0.1 *G* on the toe of the curve and 1.0 *G* on the shoulder of the curve. *G* is the average gradient measured between these two limiting points. For full discussions of the characteristics of printing papers, and the problems of tone reproduction, the reader is referred to the papers by Jones and his collaborators,²² and to the book by Mees.³⁰

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Chapter V

PHOTOGRAPHIC SENSITIZING FOR THE INFRARED

Practically all materials used in photography consist of a suspension of minute crystals of a halide of silver in a colloidal medium which is usually gelatin. The halides employed are the chloride, bromide, and iodide of silver. The chloride finds its application primarily in papers for making photographic prints by contact printing, in lantern-slide plates, and in some materials giving high contrast and used by photoengravers instead of wet plates. The bromide, although used also in enlarging papers, films for positive transparencies, and some lantern-slide plates, is the basis of all the films and plates employed for making negatives in the camera. In the majority of these, particularly where high sensitivity to light is desirable, the silver bromide contains a small percentage of silver iodide. The iodide alone, used originally in the daguerreotype process, is now used only in photoengravers' wet plates, suspended in collodion.

The photographic process is a photochemical reaction. There is a basic law of photochemistry, known as the Grotthus-Draper law, from which it follows that only the radiation which is absorbed by a system can bring about a photochemical change in it. That is, it is only the light absorbed by the silver halide in a photographic plate or film which can bring about the chemical change which makes the material darken in a developer. The radiation absorbed by the silver halides is confined to the invisible ultraviolet and to the shorter wavelengths of the visible spectrum adjacent to it. The extent of the sensitivity in the visible part of the spectrum differs from one silver halide to another. In the case of silver chloride and iodide, it extends through the violet and part of the blue. That of the bromide includes the whole of the violet and blue and part of the green. By giving very long exposures it is possible to extend these limits

somewhat, but they may be taken as applying to all practical exposures.

None of the silver halides alone responds to yellow or red light—a fact which enables us to use a red light in the darkroom for handling ordinary films or plates, and which causes red subjects to appear dark in a photograph. If a small percentage of iodide is used in the silver bromide, the response is extended somewhat further into the green, but the green sensitivity is actually quite low. There are a few special methods whereby the sensitivity of an ordinary silver halide emulsion can be extended considerably, but they are very difficult to execute, are very uncertain, and cannot be regarded as of practical value.

In 1873 H. W. Vogel, working in Germany, made the very far-reaching discovery that he could extend the natural sensitivity of the silver halides by means of dyes. Here is his story in his own words: ⁶³⁻⁶⁵

In the year 1873 the writer [Vogel] made some photographic studies of the action of the sun's spectrum on silver chloride, bromide and iodide layers. During the course of these he tested some commercial English silver bromide dry plates, the coating on which was colored yellow with an unknown dye to eliminate the reflection from the glass. In the photography of coloured subjects these plates showed not the slightest difference from ordinary photographic plates. They reproduced blue as light, and yellow and red as dark. They behaved quite differently towards the sun's spectrum. While the sensitivity of silver bromide decreased gradually from the blue to the green, the plates concerned showed a decrease toward the green and then an increase in the green itself. An inquiry addressed to the manufacturer of the plates, asking if he knew anything of their behavior in the spectrum, drew the reply that he did not know the slightest thing about it.

Vogel concluded that the added dye was producing the unexpected result and that the absorption of green light by it was playing a part in the process. He then made a study of dyes with the object of finding some which would produce this valuable extension of sensitivity. The first dye selected was Coraline, which was found to make a plate sensitive to yellow light. It was discovered next that certain green aniline dyes, which absorbed red light, made a plate respond to the red. He wrote: "From these results I believe I can conclude with relative certainty that we are in a position to make silver bromide sensitive

to any desired color, or to increase any sensitivity to color which may be present." Vogel had made one of the outstanding achievements in the history of photography in finding a way of correcting the oldest deficiency of the photographic process—its inability to render color values correctly.

The work of Vogel naturally excited much interest and also was subjected to considerable opposition and ridicule. Further study, however, showed with certainty that some dyes could exert a definite sensitizing action, although this did not apply to all dyes. For example, while Vogel found Coralline, Fuchsin, Naphthaline Red, Aldehyde Green, Methyl Violet and, particularly, Cyanine to be effective, the dyes Indigo and Aniline Blue, which strongly absorb red light, did not sensitize at all. It was also found that the sensitizing action of a particular dye depended to some extent on the nature of the silver halide with which the plate was coated, and also on whether collodion or gelatin was used as the suspending medium.

Becquerel in 1874 found chlorophyll to be a sensitizer, and the next year Waterhouse selected Eosin, sent to him among other dyes by Vogel, as being a very satisfactory sensitizer for the green. Eosin and its derivatives turned out to be very important sensitizers, especially for silver bromide plates. Waterhouse actually used Eosin with silver bromide-collodion plates, but the particular sensitizing action of the dye with silver bromide-gelatin plates was discovered and patented in 1882-83 by Clayton and Tailfer, and plates sensitized with Eosin were placed on the market under the name of *Isochromatic* plates. For many years they were the only color-sensitive plates generally used for practical photography.

Study of the sensitizing dyes was pursued actively by Vogel, Schumann, Eder, and others, and in 1884 Vogel found Quinoline Red to be a satisfactory sensitizer for the yellow-green and orange. Plates sensitized with a mixture of Quinoline Red and Cyanine were sold as *Azalin* plates. Vogel also found that, if Eosin was used as its silver salt dissolved in ammonia, particularly powerful sensitizing resulted, and Eosin-silver plates appeared on the market in Germany.

In the same year Eder discovered the superior sensitizing power of Erythrosin (a relative of Eosin, being its iodine ana-

logue) for the yellow-green. When used as its silver salt, it was the most powerful sensitizer available for this part of the spectrum, its maximum sensitivity being at 5,650 Å.

Relatively few of the dyes investigated, however, found applications in practical photography, the only ones used to any extent being Eosin, Quinoline Red, Cyanine, and Erythrosin. The last-named was used practically exclusively as the sensitizer for orthochromatic and isochromatic films in the early thirties. Certain other dyes were used for the photography of the spectrum, however. In 1891 Higgs, in his exhaustive study of the spectrum of the sun, sensitized an emulsion to the extreme red and near-infrared radiation using the bisulphite compound of Alizarine Blue, and in 1900 Lehmann used this dye in conjunction with Nigrosine and others and recorded the spectrum to beyond 9,000 Å in the infrared. It is not certain that Alizarine Blue was entirely responsible for Higgs's results, since it contained bisulphite, which is known to extend spectral sensitivity somewhat. Eder and Valenta tested many dyes and recommended certain of them for photography of the red end of the sun's spectrum. They included Diazo Black BHN, several of the Wool Blacks and Columbia Green, with which the furthest extension into the red end of the solar spectrum was obtained. A serious defect of many of these old sensitizers was their desensitizing action, so that, although they conferred sensitivity to the longer-wavelength regions of the spectrum, sensitivity to white light was materially reduced.

A new era in photographic sensitizing for the green and red started in the period 1902-06.^{23, 39-43} In 1902 Miethe and Traube discovered the sensitizing action of the isocyanines, particularly Ethyl Red, an analogue of Cyanine which had been found to sensitize some years before. Ethyl Red was superior to Cyanine as a sensitizer, and emulsions made with it were not subject to the fogging and bad keeping associated with Cyanine Blue. Up to about 1900 the dyes used in sensitizing studies were commercial specimens, generally used unpurified. It is known now that the impurities present must have had a most deleterious effect in many cases. This was recognized by Miethe and Traube, who were the first to make dyes specifically for use as sensitizers. Their work marks the beginning of the modern era in this field.

Shortly after the discovery of Ethyl Red, Koenig, of the Hoechst Dye Works, produced a whole series of dyes in rapid succession. These were of the isocyanine class, and those of the greatest interest were Orthochrome T, Pinaverdol, and Pinachrome. They were all excellent sensitizers for the green and orange, but the first true sensitizer for the whole of the visible red was not discovered until 1904, when Homolka, also at the Hoechst Dye Works, made Pinaacyanol.

These discoveries laid the foundations of "panchromatic" photography; Pinaacyanol, the most important sensitizer for the red, was used in all panchromatic materials until the thirties. Although by itself it gives fairly good sensitivity in the green in addition to its major contribution in the red, it was usually employed in conjunction with other dyes such as Orthochrome T, Pinaverdol, or pinachrome which conferred greater response in the green. After the discovery of Pinaacyanol, progress was relatively slow. Much study was devoted to producing new sensitizing dyes, but most of it was concentrated on the introduction of substituents into known dyes. The chemical structure of the dyes was not elucidated, and this undoubtedly acted as a barrier to systematic progress.

The next impetus came during and just after the Great War (1914-18), when the supply of dyes was cut off from countries outside Central Europe. This was a serious problem, for sensitizing dyes were needed badly to make panchromatic plates for aerial photography. At Cambridge, Sir William Pope and his colleague, W. H. Mills, studied the problem, and soon worked out methods for the manufacture of the required dyes. They went further, however, and Mills made a very thorough investigation of the chemistry of the cyanine dyes, and he and his pupils published the results in a series of brilliant papers from 1919 to 1928. This work of Mills was instrumental in putting the chemistry of the cyanine dyes on a firm foundation. Many hundreds of sensitizing dyes of the cyanine class are now known.

During the Great War, Pope and his colleagues prepared Pinaverdol and Pinaacyanol (also known as Sensitol Green and Sensitol Red, respectively). In 1919 the Hoechst Dye Works made a very useful green sensitizer which they called Pinaflavol.

Three new dyes, Cyanine A, Cyanine B, and Pantochrome, were made in France by Barbier, of the Lumière Company, and in the United States the isocyanines and Pinacyanol were prepared by several workers. None of the early dyes was particularly suitable for photography of the invisible infrared. While this study was being made of sensitizers for the visible spectrum, however, there was naturally a considerable interest in extending the photographic spectrum into the infrared region, for it was of special importance to physicists and astronomers.^{23, 39-43}

The only really useful sensitizer for the infrared prior to 1919 was Dicyanine, made by the Hoechst Dye Works shortly after the introduction of Pinacyanol. It was in use until 1925, when it was replaced largely by a new dye, and at the present time it is not used at all. Meggers and Merrill at the U. S. Bureau of Standards and McLennan in Toronto used Dicyanine for spectroscopic work up to about 10,000 Å with excellent results. Its maximum effect is at 7,100 Å, but its sensitizing action falls off but slowly to considerably longer wavelengths. Dicyanine was, however, rather difficult to use. It did not keep well and was rather fickle in its behavior. Plates had to be sensitized by being bathed in solutions of the dye containing alcohol and ammonia, and many failures were experienced in their preparation.

In 1919 Adams and Haller, working at the Bureau of Chemistry in Washington, discovered a new dye which they called Kryptocyanine. It sensitizes very strongly between 7,000 and 8,000 Å, with a maximum near 7,500 Å. It is stable and easy to use, and can be added to an emulsion during manufacture so that plates and films sensitized with it can be made for commercial purposes. For many years plates and films sensitized by Kryptocyanine were the only infrared materials available on the market. Ball¹ described its use in 1925 for preparing infrared-sensitive motion-picture film. It renders photography of the spectrum to 8,000 Å very easy and has been much used for plates and films for haze penetration in aerial and landscape photography. Beyond 8,000 Å, Kryptocyanine has very little sensitizing power, less even than the older Dicyanine at 9,000 Å.

The next step forward was in 1925, when H. T. Clarke at the Kodak Research Laboratories, while preparing Kryptocyanine,

noticed that a second less soluble dye was formed during the reaction. It was found to sensitize from 6,500 Å to 9,000 Å for moderate exposures, and was termed Neocyanine. By ammonia treatment of plates sensitized with the dye, it was possible to photograph the spectrum to well beyond 10,000 Å. In 1930 using Neocyanine plates, Babcock, of Mount Wilson Observatory, photographed the solar spectrum as far as 11,634 Å, the farthest limit that ever had been attained photographically. Babcock also made the first photograph in total darkness using invisible heat rays, the plate being sensitized with Neocyanine.

Up to the end of 1931, Neocyanine was the best sensitizer known for the photography of the extreme infrared, and with it the furthest extensions of the spectrum had been photographed.

During the period after the First World War, there had been developing an intensive investigation of sensitizing dyes, and this culminated, in the years 1931–35, with an outcrop of a large number of very good sensitizers for the infrared, which rendered obsolete all those previously known, with the exception of Kryptocyanine.^{7, 17, 24, 41} One new group of sensitizers of outstanding importance, called the tricarboyanines, was discovered during this period. These dyes are very powerful sensitizers for the infrared, and they made it possible to photograph the spectrum to beyond 11,000 Å. Of the tricarboyanines, the one having the furthest extension of sensitivity in the infrared was Xenocyanine, which has its sensitizing maximum at about 9,600 Å. When this dye was used, the spectral region between 9,000 and 11,000 Å became readily accessible, and, in particular, Meggers and Kiess, at the U. S. Bureau of Standards in Washington, succeeded in photographing many hundreds of new spectral lines out to about 12,000 Å.

In 1934, a still further extension of photography into the infrared became possible as the result of the development of the tetra- and pentacarboyanines.^{8, 18, 19} Systematic investigations led to the production of commercial photographic plates sensitive in the infrared to beyond 13,000 Å. Those in common use at the time of writing have their sensitivity maxima at about 9,800 Å and 11,000 Å. They have enabled Babcock in the United States and Herzberg in Germany to photograph the spectrum of the sun out to about 13,600 Å, and Meggers at the Bureau of

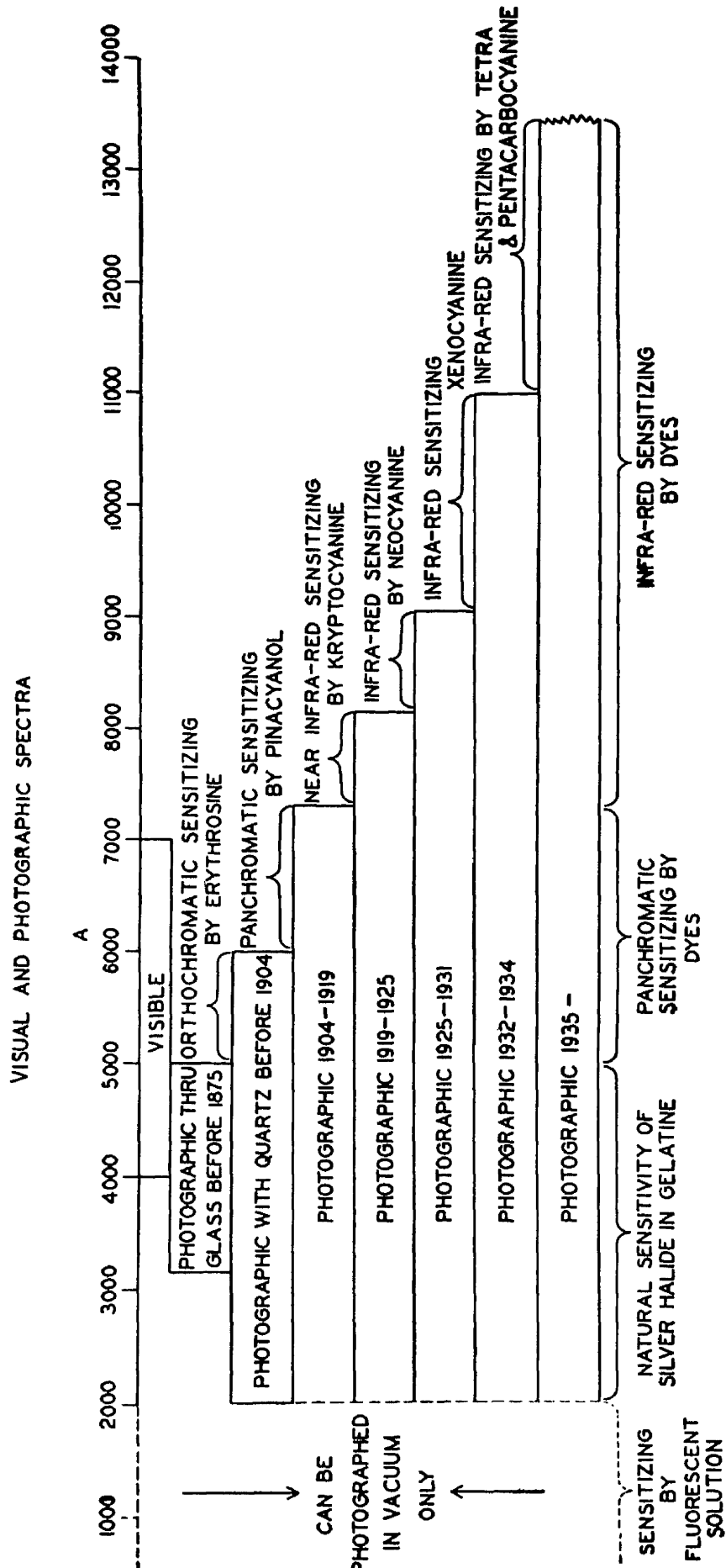


Fig. 16. Chart showing the progress of photographic sensitizing.

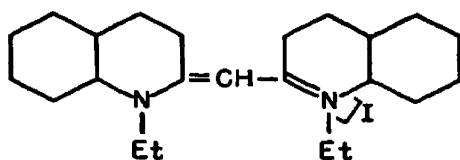
Standards to record many hundreds of new lines in the spectra of the rare gases to beyond 13,000 Å (see Chapter XII).

In the form of a chart, the progress which has been made in photography of the spectrum as the result of the advances in the knowledge of sensitizing dyes is shown in Figure 16.

CONSTITUTION OF THE SENSITIZING DYES

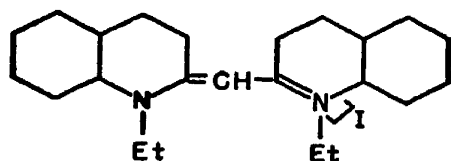
For the interest of those who have some knowledge of chemistry, a brief discussion of the constitution of the important series of sensitizers is included. No attempt is made to deal with the methods of preparation of the dyes. Those interested should refer to the works mentioned in the bibliography at the end of the chapter. For the survey which follows, I am indebted to Dr. L. G. S. Brooker, to whom much of our present knowledge of sensitizing dyes is due.

Most of the modern photographic sensitizing dyes belong to the cyanine and related series, which are derived from organic bases containing nitrogen.^{7, 17, 23, 33, 43} All the dyes have certain features in common, and in order to understand the essential characteristics of the group, it will be convenient to examine the formula of a typical member:

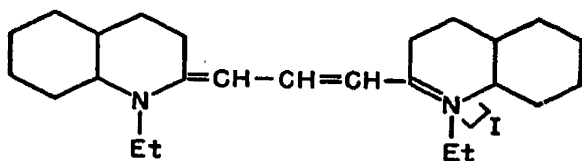


It will be seen to have a complex molecule, consisting of two nuclei joined together by a bridge consisting of a CH group. The nuclei are of the organic base, quinoline, and both contain nitrogen atoms, one of which is tertiary and the other quaternary. An alkyl group is associated with each of the nitrogen atoms, and an acid radical with the quaternary nitrogen atom.

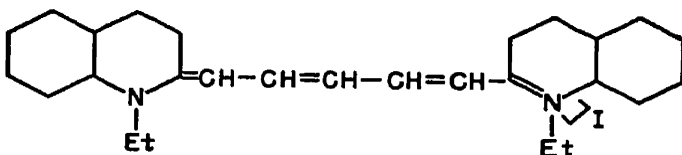
Examination of the preceding formula will show that there is a chain of carbon atoms going from one nitrogen atom to the other. Within this chain there are alternate single and double bonds, and this type of chain is called a conjugated chain. Such a chain is usually found in molecules of colored substances.



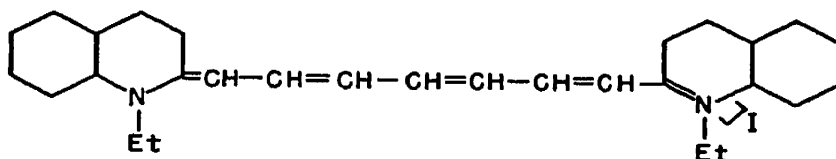
(I)



(II)



(III)

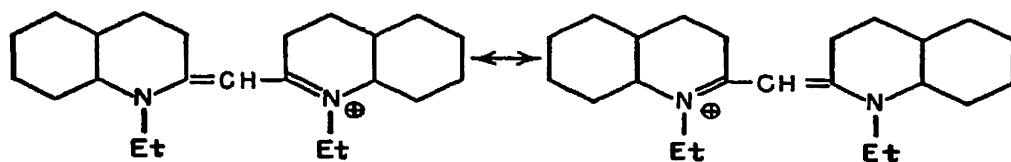


(IV)

Here are four related cyanine dyes, of which the one already considered stands first. In each case there are two quinoline nuclei, and the nitrogen atoms are linked by conjugated chains containing an uneven number of carbon atoms. However, as we go from I to IV, the chains get longer, increasing from 3 carbon atoms in I, through 5, and 7, to 9 carbon atoms in IV, counting in each case from one nitrogen atom to the other. The carbon chains increase in length by two each time. The nomenclature of the dyes is based on the length of the chain which joins the two nuclei, and not the nitrogen atoms. Dye I is known as a simple cyanine, II is a carbocyanine, III is a dicarbocyanine, and IV is a tricarbocyanine. In the simple cyanine (I) the nuclei are joined by one CH group; in the carbocyanine (II) there is a 3-carbon chain; in the dicarbocyanine (III) the chain has 5 carbon atoms, and in the tricarbocyanine (IV) there is a 7-carbon chain joining the two nuclei.

In a dye there is much evidence for supposing that the acidic radical of the dye is not associated with one nitrogen atom more

than with the other. Otherwise expressed, the positive charge of the dye cation is shared between the two nitrogens. There exists, in fact, a kind of tautomerism within the molecule represented by



but only a charge changes position, and not an atom. Ionic tautomerism of this kind is termed resonance. However, it is not considered that there is actual oscillation between the two forms, but rather that the molecule is a hybrid between the two extremes. Most of the known dyes, including the cyanines, can be written as resonating structures.

The dyes so far considered have nuclei of quinoline. It is possible to make very useful variants of these dyes by substituting other nuclei, such as benzoxazole, benzothiazole, benzoselenazole, thiazole, thiazoline, naphthothiazole, 4-methylthiazole, 4-phenylthiazole, and dimethylindolenine, the formulas for which follow (Figure 17, p. 83).

The benzothiazole nucleus yields a very useful series of dyes, and the formulas for six are shown in Figure 18.

These dyes are known as thiacyanines. In the first four, the nuclei are linked together by 1-, 3-, 5-, and 7-CH groups, as in the case of the series previously mentioned. If it were desired to go to still longer chains, as in the case of *E* and *F*, which have 9- and 11-carbon chains, respectively, it was necessary when the dyes were first made to attach an acetoxy group to one of the carbon atoms in the chain.⁸ In 1937, however, Dieterle and Riester^{18, 19} showed how to make these dyes without a substituent in the chain (see p. 84). The difficulty of making the dyes increases as the chain gets longer, and finally they are very unstable indeed. There is a wide range of colors in the dyes. They and the dyes related to them provide the most useful range of sensitizers known at the present time and include sensitizers for the infrared. The dye *E*, with the 9-carbon chain, is known as a tetracyanine, whereas *F*, with an 11-carbon chain, is a pentacyanine.

Table VIII, on pp. 85–6, shows the structural formulas for a number of infrared sensitizing dyes which have been used in practice, together with the wavelengths at which they show their maximum spectral absorption in methyl alcohol and confer their maximum sensitizing on a photographic plate.⁶⁶ Particulars are

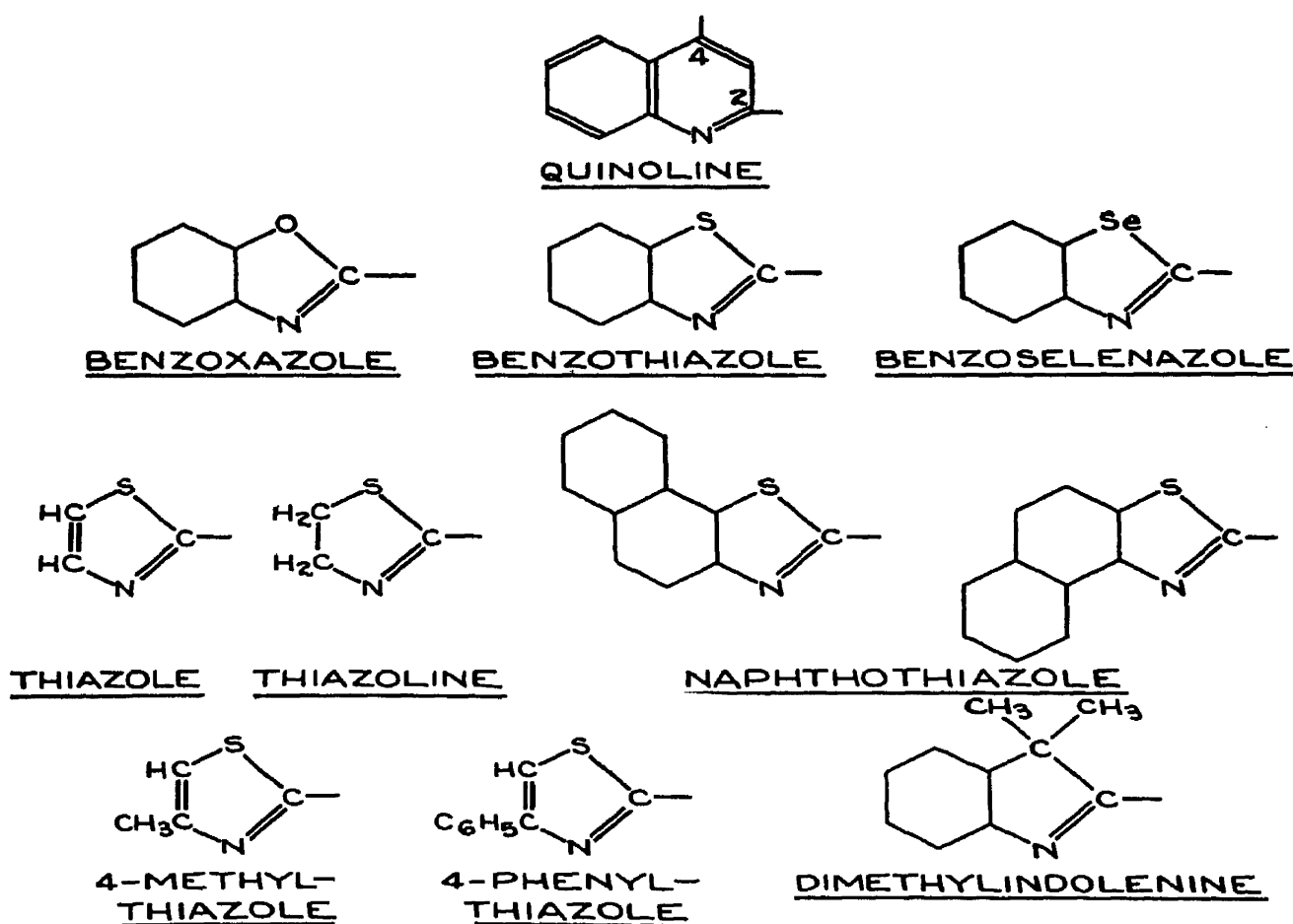


FIG. 17. Nuclei used in sensitizing dyes.

also included for three of the earlier red sensitizers—Cyanine, Ethyl Red, and Pinaeyanol. The limit of sensitizing extends generally to wavelengths considerably longer than that of the maximum. It is not possible, however, to state what this limit is, since it depends on the actual sensitivity of the plate and the exposure which is given. Further, the position indicated for the maximum absorption should be taken only as a guide, since its location depends on the nature of the solvent used in making the solution of the dye and on other factors.^{5, 28, 49} For an idea of the limits of response of plates sensitized with some of these dyes, reference should be made to the curves given on pp. 88–90.

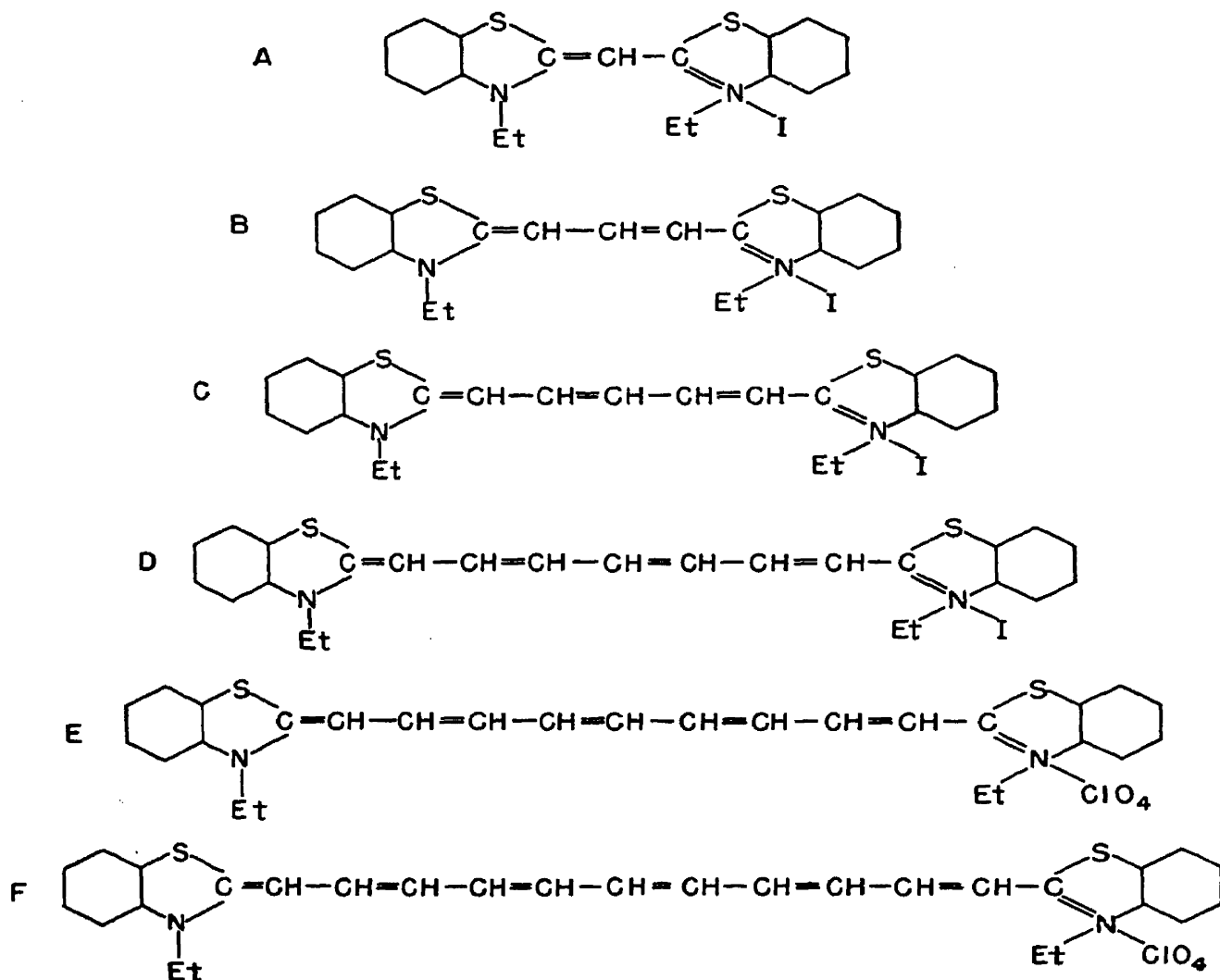


FIG. 18. Formulas for six sensitizing dyes containing the benzothiazole nucleus.

There are some differences in nomenclature of infrared sensitizers between common English and German usage. The following shows the most important of these:

<i>English</i>	<i>German</i>
Kryptocyanine	Rubrocyenin
Neocyanine	Alloccyanin
Dicarbocyanine	Penta-carbocyanin
Tricarbocyanine	Hepta-carbocyanin
Tetracarbocyanine	Nona-carbocyanin
Pentacarbocyanine	Undeca-carbocyanin

In 1937 Dieterle and Riester^{18, 19} described methods of preparing tetra- and pentacarbocyanines not substituted in the poly-

TABLE VIII

STRUCTURAL FORMULAS OF THE CHIEF RED AND INFRARED SENSITIZING DYES,
WITH WAVELENGTHS OF MAXIMUM SENSITIZING AND MAXIMUM ABSORPTION
IN METHYL ALCOHOL SOLUTION

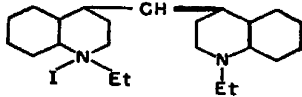
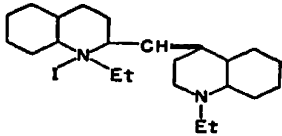
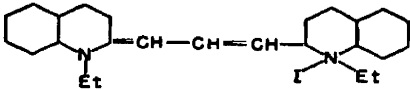
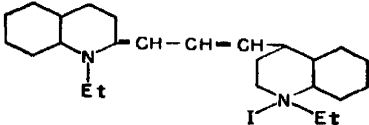
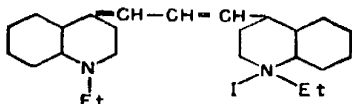
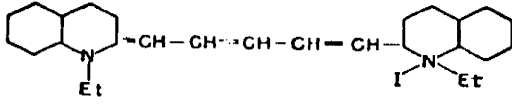
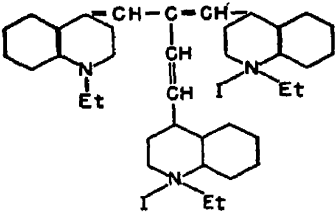
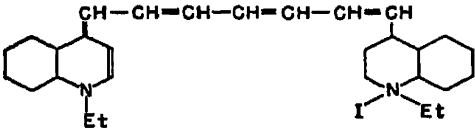
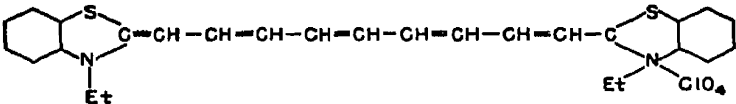
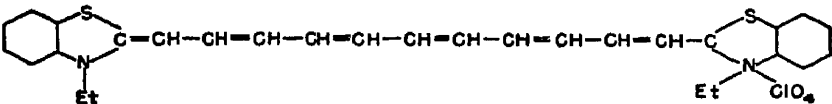
<i>Dye</i>	<i>Absorption Maximum in A</i>	<i>Sensitizing Maximum in A</i>
 CYANINE (1,1'-DIETHYLCYANINE IODIDE)	5,950	5,600 and 6,100
 ETHYL RED (1,1'-DIETHYLISOCYANINE IODIDE)	5,200 and 5,600	5,200 and 5,700
 PINACYANOL (SENSITOL RED) (1,1'-DIETHYL-2,2'- CARBOCYANINE IODIDE)	5,600 and 6,100	5,700 and 6,600
 DICYANINE (1,1'-DIETHYL-2,4'- CARBOCYANINE IODIDE)	5,800 and 6,600	6,250 and 7,100
 KRYPTO CYANINE (RUBROZYANIN) (1,1'-DIETHYL-4,4'- CARBOCYANINE IODIDE)	7,050	7,500
 DICARBOCYANINE (1,1'-DIETHYL-2,2'- DICARBOCYANINE IODIDE)	7,100	7,500

TABLE VIII (Continued)

<i>Dye</i>	<i>Absorption Maximum in A</i>	<i>Sensitizing Maximum in A</i>
 <p>NEOCYANINE (ALLOZYANIN) (BROOKER'S FORMULA) ALTERNATIVE STRUCTURE OF KÖNIG: THE SAME BUT WITH THE FOLLOWING BRIDGE -</p> <p style="text-align: center;"> $\begin{array}{c} \text{---C---CH---CH---} \\ | \\ \text{CH} \\ | \\ \text{CH} \end{array}$ </p>	7,750	8,200
 <p>XENOCYANINE (1,1'-DIETHYL-4,4'- TRICARBOCYANINE IODIDE)</p>	8,300 and 9,300	8,500 and 9,800
 <p>TETRACARBOCYANINE (3,3'-DIETHYLTHIATETRA- CARBOCYANINE PERCHLORATE)</p>	8,500	9,400
 <p>PENTACARBOCYANINE (3,3'-DIETHYLTHIAPENTA- CARBOCYANINE PERCHLORATE)</p>	7,800 and 9,950	10,500

methine chain. Until this time, these dyes had been made only with a substituent such as an acetoxy group in the chain. The sensitizing power of the new tetracarbo-cyanines was stated to be superior to that of the substituted dyes.

The spectral sensitivity characteristics of a series of typical commercial infrared-sensitive plates may be exemplified by those put out by the Eastman Kodak Company.²² These are shown

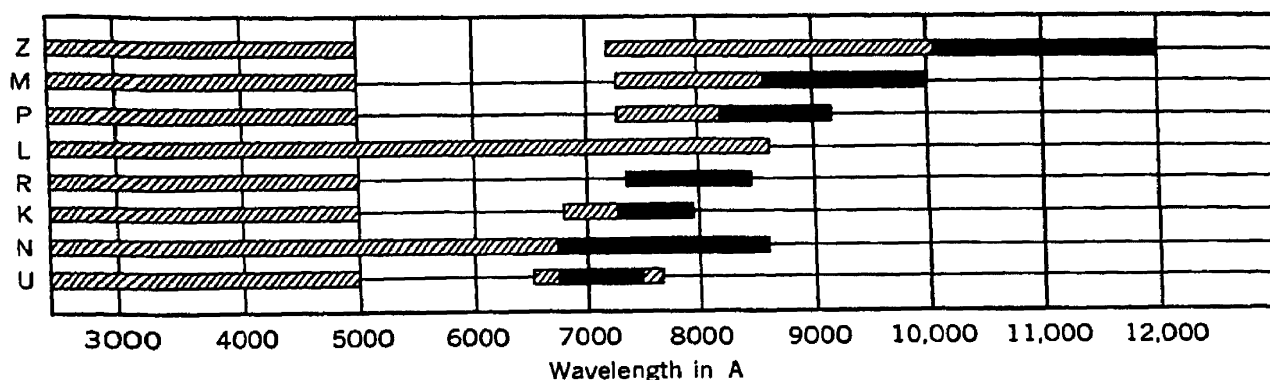


FIG. 19. Diagram of spectral sensitivity regions of Eastman Spectroscopic Plates for the infrared.

The shaded areas represent the spectral regions of total sensitivity. The black areas show the regions for which the sensitizings are particularly valuable. The classes of sensitizing are represented by the letters at the side of the diagram.

by a chart (Figure 19), which indicates in a convenient form the spectral ranges to which the plates respond, and by spectral sensitivity curves (Figure 20).

The spectral response of a film or plate is frequently shown by a wedge spectrogram, as described in Chapter IV. In Figure 12 there are shown a number of wedge spectrograms, including one for the common type of infrared film. The wedge spectrograms are response curves to the light sources by which they are made. For many purposes it is preferable to have curves showing the sensitivity to an ideal source having equal energy at all wavelengths. A series of such curves is shown in Figure 20.

Similar curves for Kodak Infrared Sheet Film and Kodak Aerographic Infrared Film are shown in Figure 21.

The spectral sensitivity curves shown in Figures 20 and 21 were determined by using an intensity-scale monochromatic sensi-

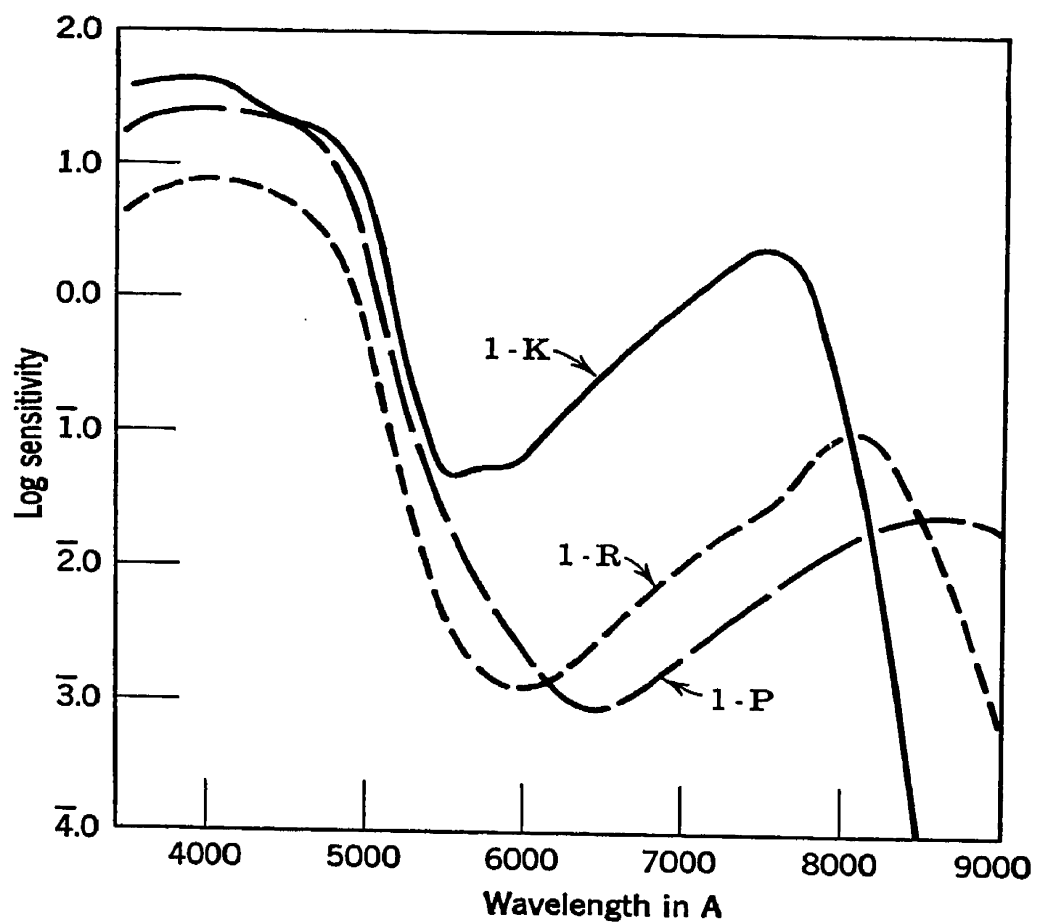
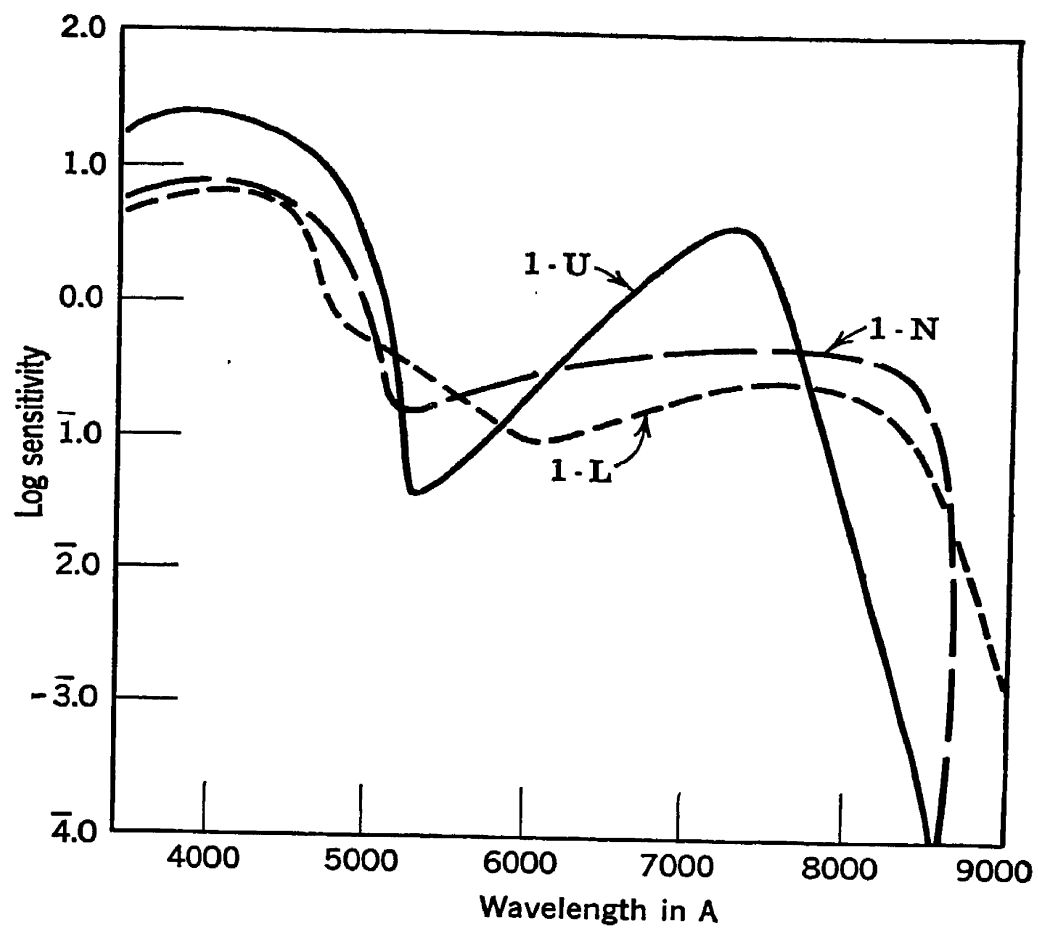


FIG. 20. Spectral sensitivity curves of Eastman Spectroscopic Plates in the infrared.

tometer. The exposure was in narrow bands of about 70 Å wide through the spectrum. The sensitivity is given in terms of the reciprocal of the number of ergs per square centimeter required to produce a density of 0.6 above fog when developed to gammas of 2.0. The sensitivity was measured at several wavelengths, and

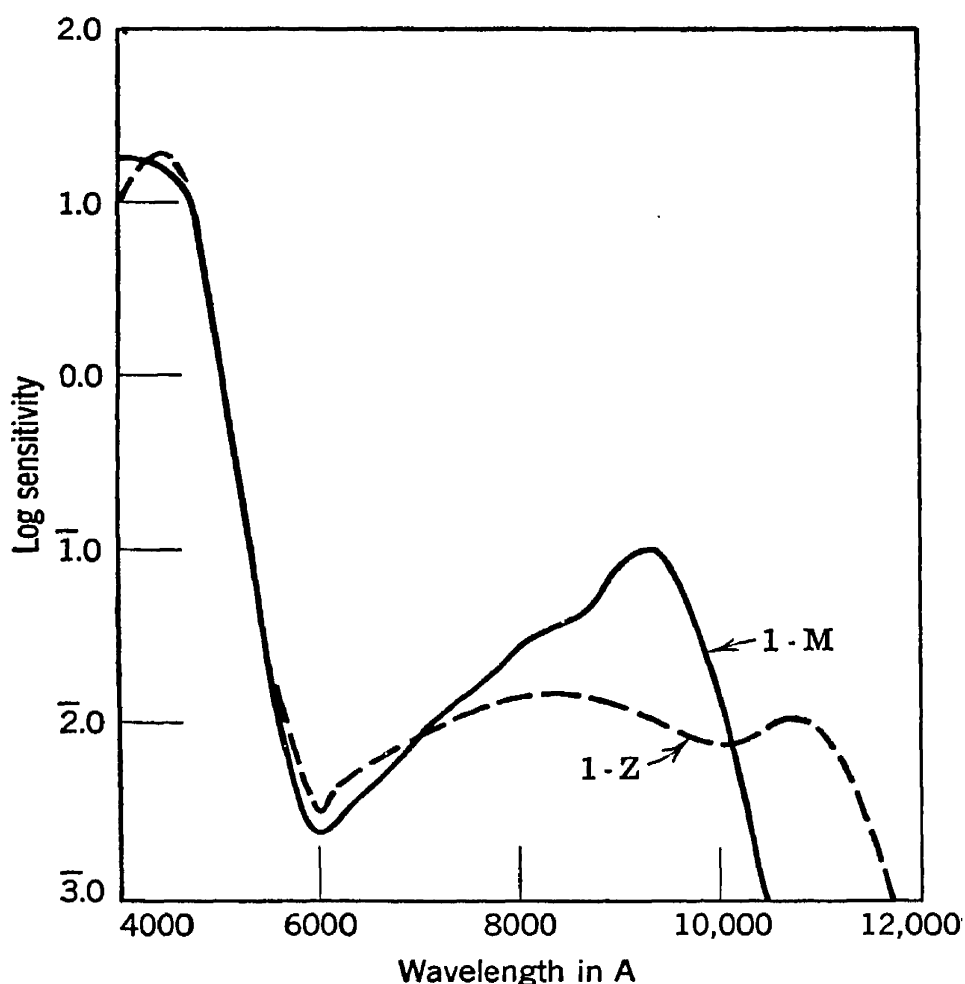


FIG. 20 (*Continued*). Spectral sensitivity curves of Eastman Spectroscopic Plates.

in the curves the logarithm of sensitivity is plotted against the wavelength.

The curves show the typical characteristics found in measurements of this kind. There is a high maximum in the blue corresponding with the maximum sensitivity of the silver bromide itself. There is a sharp drop to a minimum in the green and red, to which infrared plates are of low sensitivity. The curve then rises to a second peak, the position of which is determined by the nature of the sensitizing dye employed. The sensitivity at the

maximum conferred by the sensitizing dye is always lower than that due to the silver bromide itself.

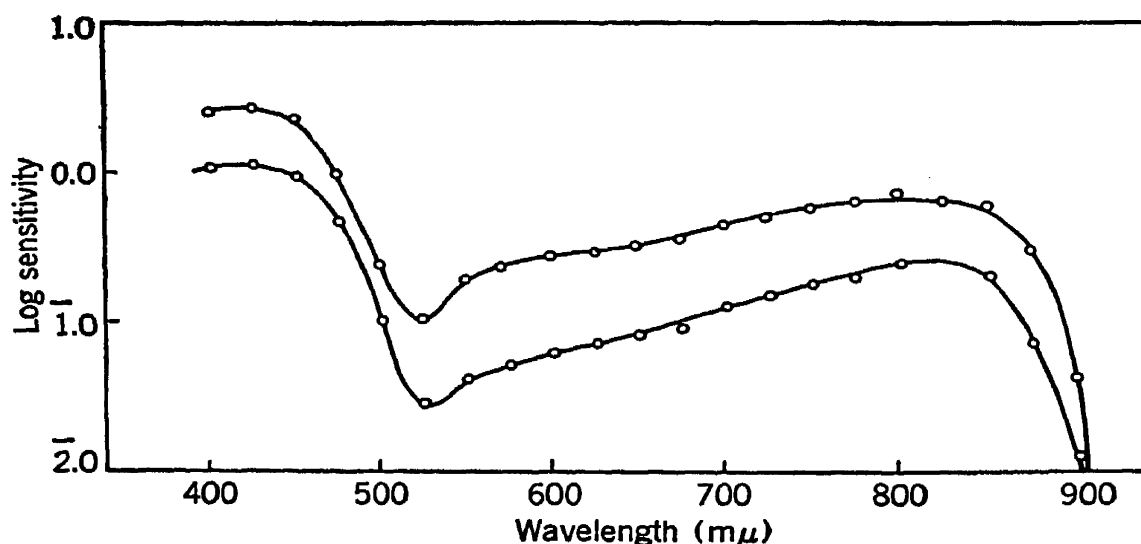


FIG. 21. Spectral sensitivity curves of Kodak Infrared Sheet Film (lower) and Kodak Aerographic Infrared Film for aerial photography (upper).

PRACTICAL COLOR SENSITIZING

Photographic emulsions are sensitized by adding the dyes at a late stage during the preparation of the emulsion, or by bathing the finished plate or film in a solution of the dye.^{21, 67} The former method leads, in general, to superior results and is the method used by the photographic manufacturer. In the earlier days of infrared photography, particularly for spectrographic purposes, the user sensitized his materials by bathing. It was not until after the discovery of Kryptocyanine that infrared-sensitive materials were made available commercially. At the present time, it is very rarely that the photographer will have occasion to sensitize his own plates. There are very few infrared-sensitizing dyes that are available on the market, the chief being Dicyanine A, Kryptocyanine, and Neocyanine. These are now very little used, and the superior sensitizers employed are not made available in the free state by the manufacturers.

It may be of interest, however, to include some instructions for sensitizing by bathing with these dyes, in case the student wishes to make some experiments. Directions for sensitizing may be found in many of the textbooks of photography; they apply to many different kinds of plates, and the techniques vary some-

what. The following instructions were published by Dundon ²¹ in 1926.

In all cases, the sensitizing and rinse baths were used at 50–55° F.

DICYANINE A. Dicyanine is very erratic in its behavior, and directions should be followed closely to get good results. Even the solid dye should be kept in a cold dark place. In order to get good sensitizing, ammonia must be added to the dye bath, and this tends to produce heavy fog. If sensitivity must be sacrificed for cleaner plates, less ammonia than recommended may be used. The sensitizing bath can be used for only a few plates as the dye soon precipitates from the solution.

Stock solution.....	1:5,000 in methyl alcohol (filtered)
Sensitizing bath.....	60 cc water
	20 cc methyl alcohol
	20 cc stock solution
	4 cc ammonia (28 per cent)

Mix the water and alcohol, and cool to 50° F. Add the stock solution, and cool the whole solution to 50° F. Wait about 5 minutes for the dye to get thoroughly mixed; then stir in the ammonia. Again wait 3 or 4 minutes before using.

Bathe the plates 4 minutes with constant agitation, drain 10 to 15 seconds, rinse 45 seconds in methyl alcohol, and dry rapidly. Plates should be dried within 5 minutes.

KRYPTOCYANINE. Kryptocyanine must be used in much lower concentration than most dyes, or fog and decreased sensitivity will result. Satisfactory results can be obtained by bathing the plates for 45 seconds in a water solution of a concentration 1:500,000 followed by a 30-second rinse in alcohol. However, the following method is better:

Stock solution.....	1:2,000 in methyl alcohol
Sensitizing bath.....	500 cc water
	1 cc stock solution
	2 cc (approximately) of 1 per
	cent solution of acetic acid

Sufficient acetic acid should be stirred into the dye solution to decolorize it within 2 or 3 minutes.

Bathe the plates for 1 minute in the sensitizing bath, rinse for 1 minute in a 2 per cent borax solution, and dry. A solution of

ammonia (4 cc of 28 per cent ammonia in 100 cc of water) may be used in place of the borax. If desired, the plates may be dried after being bathed for 1 minute in the sensitizing bath, and then hypersensitized in alkali at some later time.

NEOCYANINE.

Stock solution..... 1:2,000 in methyl alcohol
Sensitizing bath..... 75 cc water
 25 cc methyl alcohol
 1 cc stock solution

Bathe the plates for 1 minute, rinse 30 seconds in methyl alcohol, and dry as rapidly as possible. Best results are obtained if the plates dry in about 1 minute.

Although no advantage is found in the use of ammonia in the sensitizing bath, the infrared sensitivity of a Neocyanine plate can be very greatly increased by subsequent hypersensitizing.

Hypersensitizing solution..... 100 cc water
 4 cc ammonia (28 per cent)

Bathe the plates for 45 seconds, and dry rapidly.

Plates hypersensitized with ammonia do not keep more than a few days.

HYPERSENSITIZING

Special treatment of a film prior to exposure to increase its effective speed is known as hypersensitizing. It is done usually by bathing the film in a solution which will increase the sensitivity conferred by a dye sensitizer, whether it is applied in the sensitizing bath or to a film already sensitized in manufacture.^{12, 16, 32} The term hypersensitizing is usually applied to the treatment of films already sensitized by dyes. The mechanism appears to be the same, however, whether the hypersensitizing agent is applied before, with, or after the dye, and there is generally very little difference in the magnitude of the effect.¹⁰

Speed increase can also be effected after exposure, in which case it is referred to as latent-image intensification or latensification. A number of methods are available, for example, exposure to a uniform light of low intensity, treatment with sulphur dioxide gas, fuming with organic acids or mercury vapor, and treatment with hydrogen peroxide; the speed increase obtained de-

depends on the method used and on the type of film and the development. Special developers have been described which give an effective increase in speed with underexposed films of certain types; in particular, hydrazine is effective in some elon-hydroquinone developers.

It appears that hypersensitizing was discovered by Schumann in 1885.⁵⁸ He found that, if a plate was first bathed in ammonia solution, the sensitization produced by Cyanine was improved. Since that time many other hypersensitizing agents have been proposed, but ammonia is still much used in practice.

The increase in speed produced by hypersensitizing depends on a great many different factors, chief of which are the nature of the sensitizing dyes, the type of emulsion, and the procedure employed in hypersensitizing. In general, the speed of non-color-sensitized emulsions to blue light cannot be usefully increased. With emulsions sensitized to longer wavelengths, however, there is an increase in speed which is generally greater, the longer the wavelength. For example, the red speed of many panchromatic emulsions may be increased by 50 per cent or doubled by treatment with ammonia, whereas the infrared speed of infrared films or plates can be increased still more. In fact, the materials which have the farthest sensitization in the infrared can be brought to a useful speed only if they have been hypersensitized. Generalizations cannot be made, however. There are some highly sensitive panchromatic emulsions which appear to have reached their limit of speed in manufacture, for no increase can be brought about by hypersensitizing. Some infrared films are now available which have been hypersensitized in manufacture and in such a manner that they are as stable as the materials which have not been treated. This is a significant step forward, for previously it was necessary for the user to hypersensitize his films shortly before use, since they would not keep well at normal temperatures.

The simplest hypersensitizing bath is plain water,⁶⁸ which can bring about a quite significant increase in speed with some materials. Ammonia solution is one of the most efficient hypersensitizers when considered purely from the point of view of gain in speed. It has also been recommended for use when sodium carbonate is present. Another very efficient hypersensitizer is a

solution of triethanolamine, the action of which was discovered in the Kodak Research Laboratories. It is practically as efficient as ammonia, and has one notable advantage over it, in that it shows less tendency to fog, and it can be handled with less precaution. Pyridine, hydrazine hydrate, sodium sulphite, borax, and even the developer glycine (*p*-hydroxyphenylglycine), have been stated to give some speed increase. A notable speed increase sometimes can be obtained by bathing the plate in a dilute solution of silver nitrate,⁶ or silver nitrate with ammonia, and ammoniacal silver tungstate with or without hydrogen peroxide.⁵⁰ Some workers have been unable to confirm that the peroxide has any beneficial influence; in fact, it may even tend to decrease the effect of the silver salts. Caustic potash-gold chloride solutions also have been proposed by Schmieschek,⁵³ who had devised the ammoniacal silver tungstate method. A dilute solution of the antifoggant, benzotriazole, in water (40 milligrams per liter), has given a very marked increase in speed with specific types of infrared film,* but it is not generally applicable.

In 1937 Dersch and Dürr^{14, 15} described a method of hypersensitizing by means of mercury vapor, based on an effect which had first been noticed by Baukloh in 1928. The films are placed in an enclosed container in which a small amount of metallic mercury is present. Significant speed increases are claimed for panchromatic materials, the actual extent depending on the nature of the film and the conditions of treatment. The effect in practice seems rather difficult to control, and it tends to disappear if the film is kept at room temperatures. Schmieschek proposed to modify this treatment by actually immersing the film in warm mercury,⁵⁶ and claimed pronounced speed increases—in one case, using an Agfa infrared plate 850, and bathing it in mercury at 105° C for 6 seconds, he claimed a practical speed increase of about five times (nine times in threshold speed), but the plate was stable for only a few days at room temperatures. The method cannot be recommended for general practice, because the treatment is uneven, a large bath of mercury is ex-

* Unpublished observations of the late Miss H. Silberstein and B. H. Carroll of the Kodak Research Laboratories.

pensive, and mercury vapor is extremely toxic if inhaled. It is always present in the air where mercury is exposed even at room temperature, and it is present in very dangerous amounts if the mercury is warmed.

The precise mechanism by which hypersensitizing agents work is not fully understood, but the most satisfactory explanation has been given by Carroll and Hubbard.¹⁰ These investigators concluded that the result of bathing plates and films in hypersensitizing baths is a decrease in the concentration of free bromide ions in the emulsion, leaving it with an excess of silver ions. They stated that their study of the mechanism of hypersensitization served to point out the inherent limitations of the process rather than to suggest improvements in procedure. The increase in sensitivity is gained at the expense of stability of the emulsion. If the bathing is carried to excess, as, for instance, by using too high a concentration of ammonia, the films will be badly fogged and very unstable. In any case, hypersensitized materials usually cannot be kept for more than a few days at room temperature. If they are stored in an icebox or refrigerator, they may be preserved for several months before they are too badly fogged to be of use. Much depends, however, on the use to which they are to be put. For instance, in some kinds of spectrographic work, all other properties may be sacrificed to sensitivity, and it is possible to work with plates having a fog which would be intolerable for general photographic use.

The selection of a hypersensitizing bath for practical use will be governed by the increase in speed desired, considered in conjunction with the amount of fog and general instability of the emulsion which can be tolerated. From a study of hypersensitizing baths which have been proposed, it appears that needs of practice can be covered by ammonia, ammonium carbonate, triethanolamine, and water. For the hypersensitization of infrared-sensitive plates, the following formulas have been recommended by manufacturers:

AMMONIA. Bathe the plate for 1 minute in a 4 per cent solution of 28 per cent ammonia (that is, 4 parts of 28 per cent ammonia to 100 parts with water) at a temperature not exceeding 55° F (13° C). Dry rapidly.

TRIETHANOLAMINE. Bathe the plate for 2 to 3 minutes in a 0.25–0.5 per cent solution of triethanolamine at a temperature not exceeding 55° F (13° C). Dry rapidly.

AMMONIUM CARBONATE.

	<i>Avoirdupois</i>	<i>Metric</i>
Stock solution: Sodium carbonate (cryst.)	770 grains	80 grams
Ammonia solution (conc.)	770 grains	80 cc
Distilled water to	20 fluid oz.	1,000 cc

Dilute for use with 20 to 40 parts of water. Bathe for 5 minutes in fresh solution at a temperature not exceeding 53° F (12° C). Dry rapidly.

WATER. Wash plates for 5 minutes in clean running water from the faucet at a temperature not exceeding 59° F (15° C). Then wash in two changes of fresh methyl alcohol for 1 and 3 minutes, respectively. Dry rapidly.

It is very important to keep the temperature of the bath low in all cases. After being hypersensitized, the plates should be dried as rapidly as possible. They may first be transferred to a bath of methyl alcohol for a few minutes. Sometimes a bath of equal proportions of methyl alcohol and water is recommended. Whether an alcohol bath is used or not, the plates should be dried as quickly as possible in a blast of air from an electric fan. If a fan is not available, the plates which are sensitive to the shorter wavelength infrared may be dried carefully by warm air, as from a radiator.

In hypersensitizing, care must be taken to ensure that the bath acts as uniformly as possible over the plate; otherwise streaks may result. The air used for drying should be free from dust, or the plates will be spotted.

Very little quantitative work has been published on hypersensitizing, and much of that which has been published is scrappy, or too specific, or inconsistent. The interested reader should refer primarily to the papers of Carroll and Hubbard,¹⁰ Charriou and Valette,¹² Mecke and Zobel,³⁸ and Schmieschek.^{50–56} It should be emphasized again that the amount of quantitative work which has been done, or at least the results which have been published, is inadequate to permit generalizations.^{10, 37, 38} Moreover, statements made by one laboratory should not be taken as applicable

to another, for the chances are that the slight differences in conditions may lead to quite diverse evaluation of the speed increases.

LIMIT OF INFRARED SENSITIZING

The present limit of direct photography in the infrared is at about 13,500 Å. It would be unreasonable to suppose that it is not possible to make sensitizing dyes which would render a plate sensitive still further out. There is, however, a very strong absorption by the water vapor of the atmosphere which starts at about 14,000 Å, and this would seriously hinder, or actually prevent, photography between this wavelength and 15,000 Å, in free air. Beyond 15,000 Å there appears another factor which would interfere seriously with the preparation and handling of photographic materials. There is present in space at ordinary temperatures a considerable amount of what can be called "dark space radiation," which is of long wavelength, would fog plates sensitive to it, and would also probably interfere with the chemical reactions involved in the manufacture of the dyes required to make the plates respond to its wavelength. At room temperature this radiation could not be ignored, and, if it were desired to photograph out to, say, 40,000 Å or beyond, the space radiation would affect the plate during the time that the exposure was being made to the desired source. Even when the plate was not being deliberately exposed, it would be affected by the radiation unless it were kept at a very low temperature. It obviously would not be possible to do this at all stages of its preparation and handling.

In connection with this dark space radiation, Czerny¹³ has made some interesting observations. Table IX, taken from one of his publications,¹³ shows how the external conditions change as the infrared is traversed. The first column gives the wavelengths (λ) in μ ($1 \mu = 10,000 \text{ Å}$). The second column shows the number of quanta of radiation at each wavelength which fall in each second, on both sides of an area of 1 sq cm as dark space radiation in a room at a temperature of 17° C. In order to give a clearer picture of the significance of this, a calculation is made of the distance at which a Nernst burner would have to be put, so that the number of quanta falling on 1 sq cm in 1 second is

the same as that given in column two. These values are given in the third column.

TABLE IX
ENERGY OF DARK SPACE RADIATION

λ	<i>Dark Quanta</i>	<i>Equivalent Distance</i>
$\leq 1 \mu$	3.0×10^0	3,330 km
1–1.5 μ	1.9×10^7	1.36 km
1.5–2 μ	4.0×10^{10}	29 m
2–2.5 μ	3.6×10^{12}	3 m
2.5–3 μ	7.0×10^{13}	71 cm
3–4 μ	2.4×10^{15}	12 cm

It is thus clear that, in using a material sensitive to the long wavelengths, there would be considerable fogging due to the dark space radiation. In the region from 30,000 to 40,000 Å, the fogging would be equivalent to the exposure by a Nernst burner placed only 5 in. from the plate. It would appear, therefore, that without very special precautions—which might even be impracticable to carry out—it would be pointless to attempt to record wavelengths in the region 20,000 to 40,000 Å. The action of the dark space radiation would obliterate the true photographic record.

In addition to this effect of thermal radiation, there is another factor which must be taken into account. It was mentioned by Czerny and considered in detail by Kornfeld.³⁴ It involves the reaction which the molecules of the sensitizing dyes would undergo as a result of absorbing infrared radiation when in thermal equilibrium with the surroundings. The absorption of this energy might result in making the silver halide developable. Kornfeld made calculations of the velocity of this reaction as compared with the reaction velocity produced by actual exposure. They showed that infrared sensitizing would be impractical at a wavelength of 20,000 Å, where the effects of dark space radiation do not interfere seriously. With dyes capable of sensitizing at this wavelength, the thermal velocity at room temperature would be such as to affect the plate in a few minutes in the dark. It would seem that it would only be possible to sensitize efficiently by dyes at 20,000 Å, and beyond, if dyes were available which had

a much lower spontaneous reaction velocity than it seems probable to attain.

PHOTOTHERMOGRAPHIC AND THERMOGRAPHIC REACTIONS

It is perhaps legitimate in a book on infrared photography to mention color changes that some materials undergo on being heated, with or without preliminary exposure to light. It is well known that some chemical compounds, for instance, mercuric iodide, change color on being heated to a certain temperature, and revert to their original color on cooling. A double compound of the iodides of mercury and copper, in fact, was used as a "thermoscope," to indicate temperatures by its change in color. Some compounds will form a latent image on exposure, particularly to ultraviolet, which is developed to a visible image on heating. A number of these have been described by Sheppard and Vanselow,⁶² particularly silver and mercurous oxalates, silver and lead formates, lead thiocyanate, the orthoarsenite of silver and other metals, and a variety of other mercury compounds, especially mercurous azide, thiocyanate, and chloride hydrazine. These are called photothermographic compounds.

Sheppard and Vanselow⁶² described another range of compounds which they called "thermographic," and which change or develop a color when heated alone. Oxalates again are used, but they are sensitized by a polyhydroxy alcohol such as glycerin, propylene glycol, and glucose. The thermographic reaction may be catalyzed by certain additions. It is possible that some of these mixtures could be used for photographic thermometry utilizing their direct darkening or coloring under heat.

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Chapter VI

THE HERSCHEL EFFECT AND INDIRECT METHODS OF INFRARED PHOTOGRAPHY

There are five known methods for the photography of the infrared region of the spectrum. Two of these are direct, and three are indirect. In the indirect methods the records are made on a surface which is photographed later on a normal photographic material. The chief direct method consists in the use of photographic emulsions specially prepared, or sensitized to the infrared by means of dyes. The use of such sensitizing dyes has been discussed in the preceding chapter. The second direct method, which was chronologically the second to be used for infrared recording, depends on the fact that exposure to infrared is able to destroy the effect of a previous exposure to light of shorter wavelength. This is the so-called "Herschel effect."

Of the indirect methods, one, which was the first to be employed in recording the infrared, depends on the volatilization of a thin layer of material when it is warmed by exposure to the infrared. Another makes use of the ability of the infrared to extinguish the glow of a phosphorescent screen which has been excited by exposure to light of shorter wavelength. The third and most recent method depends on the use of the so-called electron-image tube.

Although the second direct and the first two indirect methods are of little value for photographing in the region of the spectrum to which photographic plates can be made to respond—being much less convenient and less sensitive—they do permit photography of wavelengths longer than those which can be recorded by specially sensitized plates. It will not be out of place, therefore, to discuss them somewhat in detail. Photography of the electron-image tube is of considerable interest. It permits pho-

tography of an image which is actually brighter than the original subject.

INFRARED PHOTOGRAPHY BY DESTRUCTION OF THE LATENT IMAGE—THE HERSCHEL EFFECT

In 1840 Sir John F. W. Herschel announced the interesting discovery that the result of exposing print-out paper to diffuse white light could be counteracted by exposing the paper to the red rays of the spectrum.⁸ Here is Herschel's discovery described in his own words:

A highly concentrated spectrum having been formed on muriated paper and kept for some time on the same spot, a colored picture was formed. On examining this picture by dispersed daylight, I now for the first time noticed that, in all that part of the paper on which the full red of the spectrum had fallen, there was an appearance of whiteness, a sort of white prolongation of, or appendage to, the dark photographic impression, contrasting itself with the general ground of the paper which, under the influence of dispersed light from passing clouds, sky, etc., had acquired a very sensible discoloration. This discoloration had, therefore, as would appear, been counteracted by the red rays of the spectrum, which are, therefore, by no means to be regarded as inactive, but rather, at least in this instance, as exciting an action of an opposite nature to that of the blue, violet, and lavender rays.

Immediately after Herschel's publication, the phenomenon was subjected to much study, particularly by Becquerel in France.⁴ This Herschel effect applied to the reversal of the visible print-out image on silver chloride paper. Later it was found that the *latent* image produced by exposure to light of shorter wavelength could be destroyed by exposure to light of longer wavelength. This action has also been called the Herschel effect, and it has been the subject of much study for the purpose of discovering if it could be applied to practical photography. Trivelli³⁴ has called it the latent Herschel effect to distinguish it from the original visible Herschel effect.

The latent Herschel effect was reported by Draper, Herschel, Lerebours, and Claudet for the daguerreotype, and was investigated by Waterhouse and Abney in the case of wet collodion plates.^{5, 9, 16} It has often been stated, even by the highest authorities, that the effect is not observed in the case of ordinary plates unless they are bathed in dye solutions before exposure. Some

investigators have found it impossible to repeat the observations of Waterhouse and Abney, and some considered that the effect was simply one of solarization. Others have claimed that the effect can be obtained with ordinary non-color-sensitive, gelatin-silver bromide plates. Lüppo-Cramer¹⁵⁻¹⁹ has even found that some papers show it markedly, particularly if copper salts are present. There have been so many arguments and so many conflicting experimental results, that it would appear that the effect is not general, but is dependent on the quality of the photographic material used and on the conditions under which it is employed. It is certain, however, that if the right material and conditions are employed, very definite reversal of the effects of exposure to short-wavelength light can be produced by exposure to longer wavelengths.

It is a common experience in photographic practice to find that there is destruction of the image on a desensitized plate due simply to exposure to the red light of the darkroom lamp. In spite of the controversy about the existence of the effect in the case of simple materials, there is plenty of evidence that it can be obtained with plates which have been bathed in solutions of certain dyes. Waterhouse found that the effect could be increased by bathing a plate in Aniline Blue or Annatto, and he actually obtained photographs of the solar spectrum in the red and infrared by using bathed plates. In 1906 Stefanik³⁰ described to the Académie des Sciences, in Paris, some experiments in which he was able to record the solar spectrum out to about 10,000 Å, using a screen which allowed only the long wavelengths to pass through. His work attracted the attention of Millochau,^{22, 23} who was able to confirm it. This investigator found that the effect was more pronounced if his plates were bathed in solutions of dyes before exposure, and by using plates prepared in this way he obtained records of a large number of lines in the solar spectrum between 8,377 and 9,325 Å. Millochau bathed his plates in dyes which absorbed the shorter wavelengths, because his observations had led him to believe that the infrared did not penetrate the emulsion very deeply, whereas the shorter wavelength light used for the general exposure did. He argued, therefore, that dyes should be added so as to restrain penetration of the blue light without reducing that of the infrared. He ob-

tained the best results with Malachite Green. In 1924 Terenin³² published the results of exposures he had made according to the method of Millochau. His dyes were used in a concentration so low, however, that they could not exert any appreciable absorbing action in the way which Millochau thought necessary. From the large number of dyes which he studied, he found that Malachite Green, Iodine Green, and Brilliant Green gave the best results. Using a high-speed coarse-grained plate, pre-exposed to an electric lamp and bathed in a dilute solution of Iodine Green, he was able to record the spectrum out to 11,300 Å.

Lüppo-Cramer¹⁵⁻¹⁸ found that reversal of the type under consideration could be obtained if the plates were bathed in solutions of desensitizing dyes. The reversal is apparently of the same type as that obtained by Millochau and Terenin, because the dyes which these investigators used are known to be desensitizers. Lüppo-Cramer was unable to obtain the effect with high-speed plates, a result which is not in accord with that of Terenin. However, it has been confirmed by Carroll⁵ and others that the most satisfactory results are found with slow fine-grained plates. An important observation made by Lüppo-Cramer was that the reversal is enhanced by using a bath of potassium bromide solution following the dye bath, an effect which has been the subject of much study by Arens,¹ Carroll,⁵ and others. In present practice, it is customary to use potassium bromide in conjunction with a solution of a desensitizer.

Some interesting observations by Carroll and Kretchman⁶ concerned the relation between the spectral absorption of the dye and the spectral region in which reversal occurred. It appears that the results are analogous to those obtained in the case of photographic sensitizing by dyes, namely, that the region of reversal corresponds with the absorption spectrum of the dye, but shifted some 500 Å to the longer wavelengths. According to the observations of Leszynski¹³ and Trivelli,³⁴ the extent of the latent Herschel effect is dependent on the conditions of the first exposure to blue light and on the time of development.

Leszynski found that infrared exposure could cause a reversal of the density produced by light, X rays, alpha rays, and hydrogen peroxide, for ordinary development and postfixation physical development. The magnitude of the effect was independent of

the wavelength of the pre-exposing light, and, for equal energy, of the intensity of the reversing infrared exposure over a wide range of intensity. The effect was found to vary with the intensity of the pre-exposure, decreasing with lower intensities.

The results of some comprehensive experiments made in the Kodak Research Laboratories in 1924–25 by Briggs, Schoen, and Jones are of interest. They examined over 100 dyes and found the most effective to fall in the classes of the azines and the triphenylmethanes. Using Malachite Green, they were able to photograph the mercury spectrum up to the line at 10,140 Å, the exposures being about the same as those required for plates sensitized with Dicyanine. In a study of the effect of the quality of light used for the pre-exposure, they obtained equivalent results with the white light from an incandescent lamp, and the mercury lines in the blue, green, yellow, and ultraviolet at 3,650 Å. The filter used for transmitting the infrared and absorbing visible light was of notable importance. The most effective was the Wratten no. 87 filter, when used with plates bathed with Malachite Green. This filter transmits beyond about 7,700 Å. Wratten filters nos. 89 and 88, transmitting beyond 6,600 Å and 7,000 Å, respectively, did not give reversal, presumably owing to their transmission in the visible region. Two special filters, which cut further into the infrared than the no. 87, produced reversal but much less markedly than the no. 87. It appeared that the maximum reversal for Malachite Green treatment was between 7,250 and 8,500 Å. Beyond 8,500 Å it became rapidly weaker, until at 10,000 Å very little reversal was obtained.

Contrary to the results of the afore-mentioned investigators, Lüppo-Cramer¹⁵ found that reversal could be produced in the case of silver chloride papers by green, yellow, orange, and red light. He even stated that under certain conditions reversal could be obtained with blue light, although later this was found to be due to deep red and infrared transmission of his blue filter. These experiments were made without bathing the papers in solutions of dyes. It appears that the effect is most marked in the spectral region absorbed by the silver halide. The observations on plates treated with desensitizing dyes of Carroll⁵ and Miyanishi²⁴ confirm this relation clearly. In 1930 Narbutt²⁵ also obtained reversal with radiation of short wavelength, and

Mauz ¹⁹ obtained confirming results. These results are of interest in connection with the theories of the Herschel effect.

In general, observations indicate that it is not absolutely necessary to include bromide in the dye bath. For instance, Pina-kryptol Yellow can act as well in the absence of bromide as in its presence. When bromide is used, however, the amount necessary is about 0.5 to 1.5 per cent. Potassium bromide seems to be more efficient than the other alkali halides with both bromide and chloride emulsions. If the bromide concentration is too high, the results may be affected adversely. Similarly, there is an optimum concentration of dye. If it is too high, the effect may be less than at lower concentrations, whereas, if it is too low, negative-image formation may occur before reversal sets in, and at some concentrations re-reversal may set in.

The spectral distribution of the Herschel effect has been studied by Gorokhovskii and Shestakoff ⁷ and by Bartelt and Klug.³ From their work it appears that the wavelength of the reversing radiation varies inversely as the size of the latent-image nuclei. Studies of the effect of temperature on the Herschel effect have been made and are of importance for the theory of its action. There are two main theories. One of them attributes the effect to an oxidation of the silver nuclei of the latent image by oxidizing agents excited by exposure to red light. The other attributes it to a dispersion or some other physical alteration of the latent-image nuclei by the direct action of the red or infrared light. For a full discussion of the theories and the evidence on which they are based, the reader is referred to the survey in Mees's book.²⁰

The latent Herschel effect has been used in practice mainly for infrared spectrographic recording. In addition to this, however, it has found a number of other useful applications. The chief of these are for the preparation of direct positives in the camera,^{28, 38} and the making of duplicates of negative and positive images on films and plates.³¹ In this practice, it is customary to use slow materials of relatively fine grain, and to bathe them in solutions of desensitizing dyes containing potassium bromide.

Poirot and Bientz ²⁸ made pictures in the camera using Iodine Green in the concentration of 1:26,000 recommended by Terenin, and claimed better reversal if the second exposure were inter-

mittent rather than continuous, as mentioned also by Long, Germann, and Blair.¹⁴

Stockbarger³¹ described the use of the Herschel reversal to produce direct-positive prints from positive transparencies such as lantern slides. He used a high-contrast paper such as Azo no. 5, and the reversal exposure was through a deep red safe-light. He emphasized the range of contrast which can be obtained by variation of the fogging first exposure and the second red-light exposure.

Weber³⁸ obtained direct positives in the camera by the Herschel effect using chloride paper bathed in Pinakryptol Yellow, 1:2,000. The exposures were many hours for landscapes in direct sun, but the results showed the characteristics of normal infrared landscape photographs. Exposures were also made by electric light, but the shortest exposure times were claimed for silver iodide paper, made by iodizing exposed bromide paper, and bathed in Malachite Green, 1:25,000, and 1 per cent potassium bromide.

Lüppo-Cramer¹⁵⁻¹⁸ produced duplicates by using lantern-slide plates bathed in Fuchsin or Pinakryptol Yellow. Kamada¹² made photographs in this way with process plates bathed in Fuchsin. Carlton and Crabtree, in some unpublished work carried on in the Kodak Research Laboratories, obtained duplicate cinematograph negatives using Phenosafranin and positive film. In process work, good direct positives can be obtained in the camera, using process film bathed in Phenosafranin bromide.

Urbach and Sonn³⁰ in 1935 utilized the latent Herschel effect in printing negatives of high contrast, in order to reduce the contrast of the positive prints. After the normal exposure through the negative, a second uniform flash exposure was given to light of long wavelength, with the negative still in position. The effect of this is to reduce the latent image in the most exposed regions, that is, the shadows of the positive. Hertzberg⁹ also recommended a general exposure to red light to decrease the contrast in a print. He made a rather careful study of the practical aspects of the effect in printing and suggested its use for obtaining white margins on an exposed print.

In 1934 Planskoy²⁷ applied for a patent for using the latent Herschel effect in making composite pictures. He made a photo-

graph on an emulsion treated so as to facilitate destruction of the image by light of long wavelength, and then destroyed this image locally in the desired part by exposure to long-wavelength light. Another latent image was then impressed in this area, after which the emulsion was developed.

PRACTICAL PROCEDURE. In experiments made on the duplication of cinematograph negative films by the bleaching action of red light, Carlton and Crabtree found that much more satisfactory results are obtained using positive film than can be produced with negative film. Lower contrast and more latitude are given by the positive material, although there is marked lack of detail in the shadows. The film is given a flash exposure to a 30-watt tungsten-filament lamp, sufficient to result in a density on development equal to the maximum density it is desired to reproduce. The film is then bathed for 2 minutes in a 1:3,000 solution of Phenosafranin containing 1.2 per cent of potassium bromide, and then printed through the negative by means of a high-efficiency tungsten-filament lamp screened with the red Wratten filter no. 25. Final development is for 8 minutes at 65° F in the Eastman D-16 developer, which is commonly used for developing cinematograph positive film.

Carroll⁵ obtained good reversal of the spectrum well out into the infrared by using process plates pre-exposed for 15 to 20 seconds to the light from an unscreened tungsten-filament lamp at an intensity of 1.4 candle-meters. The plates were then bathed for 5 to 10 minutes at room temperature in a 1:20,000 solution of Pinakryptol Green, rinsed, and dried rapidly in a current of air. They were then bathed again in a 1 per cent solution of potassium bromide for 10 minutes, rinsed and dried, and then exposed in the spectrograph. Good reversal in the red and infrared was also obtained under the same conditions with the following dyes: Malachite Green, Malachite Green plus Auramine, Neutral Red, Safranin, Methylene Violet, Safranin B, Rosolane B, Aniline Violet, and Diphen Blue B.

The following conditions have proved satisfactory for the production of direct positives by the Herschel effect in the process camera: Eastman Process Film is flashed by exposing 4–5 seconds at a distance of 8 ft from a 15-watt tungsten-filament lamp. This exposure should be such as to give a density of 1.8–2.0 when

the film is developed in D-11 formula for 5 minutes at 65° F. The film should then be soaked for 10 minutes in water and swabbed with cotton wool to remove air bells and dust. It is then drained and bathed for 3 minutes at 65° F in: Phenosafranin solution (1:1,000), 125 cc; potassium bromide (10 per cent), 50 cc; water to 500 cc. The film is then drained and dried. Within 24 hours of desensitizing it should be exposed. If two 25-ampere white-flame arcs, a Wratten no. 25 filter, and an 18-in. lens at $f/22$ are used, and the film is to be copied to equal size, the exposure is about 30 minutes. From the moment of immersion in the desensitizer, all operations should be carried out in total darkness. After exposure, the film is developed for 5 minutes in D-11 at 65° F, rinsed, fixed, and washed until the dye stain is removed. If large films are used, they should be held flat in the camera by the use of a vacuum back or a gelatin stay-flat.

INFRARED RECORDING BY VOLATILIZATION

In 1840 Sir John F. W. Herschel^{43, 44} continued the investigation of the infrared region of the spectrum which had been discovered by his father, Sir William Herschel in 1800 (p. 5). He clearly proved that the spectrum of the sun extends beyond the visible limit and that the Fraunhofer lines are also continued into this region. He employed a very ingenious method. He prepared a surface which would absorb heat readily, by coating a sheet of very thin paper with lampblack by smoking it over a candle or the flame of oil of turpentine. To the back of the paper he applied alcohol by means of a brush and then exposed the paper to the sun's spectrum. Since the infrared part of the spectrum consists of heat rays, which are absorbed by the lampblack, the alcohol in the part of the paper on which the "heat spectrum" fell evaporated more quickly than that in the parts not exposed. In this way a record of the spectrum was obtained. It was viewed from the back of the paper, the dry parts showing against an undried darker background. If the invisible spectrum were quite continuous, the alcohol would have evaporated to leave a continuous dry strip on the paper where the spectrum fell. Herschel found that in the record he obtained three or four moist patches were left among the dry areas. These must have cor-

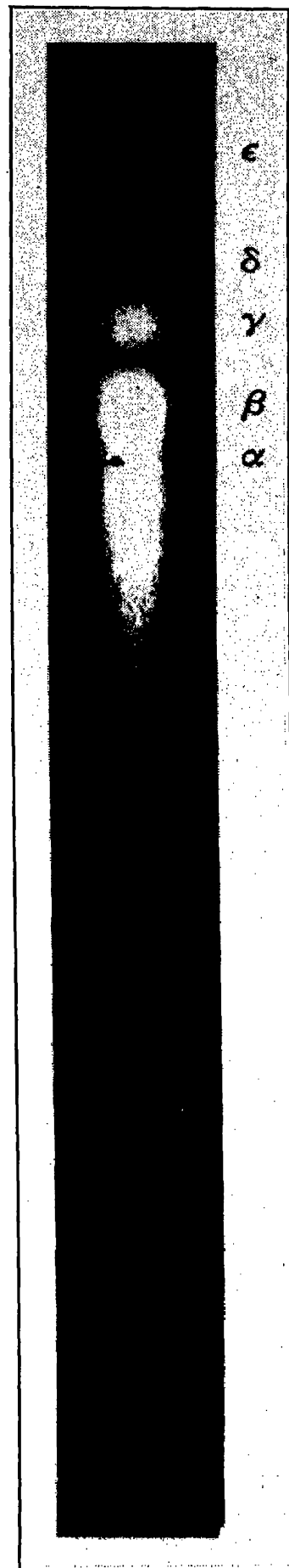
responded to parts of the spectrum in which radiation was lacking. They did, in fact, correspond to groups of absorption lines in the infrared region of the solar spectrum. Figure 22 is a copy of the actual illustration given by Herschel in his article.

Records of the spectrum obtained in this way are naturally transient, although they last long enough to enable the observer to make measurements. Herschel desired to obtain a permanent impression, or a "fixed thermograph" as he called it, and he was partly successful. Again, he employed a device of the utmost simplicity and of great ingenuity. In the alcohol used for washing the paper he dissolved the coloring matter of the Viola tricolor. The dye was deposited in the pores of the paper at those points where evaporation went on most rapidly in greater quantity than in the places where it proceeded slowly. It was accumulated at those points by successive washes of alcohol to such an extent as to indicate the distribution of the heating rays by a marked difference in color. At the present time we should photograph the record in order to obtain a permanent impression.

About 90 years appear to have elapsed before any results were again obtained by the method of Herschel. In the period 1929 and onwards, it was investigated in a modified form by Czerny and his coworkers.³⁹⁻⁴² Instead of alcohol, Czerny used solid materials, such as camphor and naphthalene, which have a high vapor pressure at room temperature.

FIG. 22. Volatilization photograph of the solar spectrum.

This is a copy of the original illustration published by Sir J. F. W. Herschel in the *Philosophical Transactions* in 1840.



The material was spread out in a thin layer on a collodion membrane about $0.1\ \mu$ thick and put in an enclosed space at low pressure and saturated with the vapor of the solid. On the back side of the membrane was a thin coating of lampblack. Any radiation which fell on the lampblack and was absorbed by it would raise its temperature. The camphor or naphthalene on the other side would then sublime away from the warmer parts and deposit on the cool unexposed places. The parts of the coating on which the radiation fell would thus become thinner, and after the exposure ceased they would remain as they were, because a stationary state is provided by a substance in equilibrium with its vapor. The change in thickness would be revealed by a change in the interference color.

Czerny worked with a low pressure in his apparatus and preferred naphthalene to camphor. Clearly, if the lampblack absorbing layer is omitted, the spectrum which is obtained is the absorption spectrum of naphthalene itself if the exposure is made to a continuous spectrum. In this manner absorption bands were recorded out to a wavelength of about 60,000 Å.

The work of Czerny was refined and extended by his students. Willenberg,^{46, 48} by using a mixture of oils—the fraction obtained in the distillation of petroleum between 260 and 280° C at atmospheric pressure—increased the sensitivity of the method about 50 times. It is important that a liquid used in this manner should spread in a uniform film on the membrane and that it should readily show interference effects. Willenberg first of all used a lampblack absorbing layer as employed by Czerny, but found later that superior results were obtained by means of a layer of bismuth black prepared by evaporation. The resolution obtainable in such a process is obviously dependent on the characteristics of the black absorbing layer. Willenberg and Czerny and Mollet⁴⁰ were easily able to separate two lines about one tenth of a millimeter apart.

By way of illustration, Willenberg showed photographs of the spectrum of mercury with lines out to 11,290 Å; bands in the rotation spectrum of hydrogen chloride at 34,600 Å; an atmospheric absorption band at 42,700 Å due to carbon dioxide; and bands in the absorption spectrum of naphthalene at 33,000 Å,

between 50,000 and 60,000 Å, and at 63,000 Å. An interesting application consisted in showing the distribution of temperature over heated bodies. The plate of a rectifying valve and a black glass bulb containing water at 90° C could be photographed quite clearly if their images were projected on the oiled membrane and then photographed in the camera.

In 1937 Czerny and Mollet⁴⁰ coined the word "evaporography" to apply to this method of photography. They showed that it is superior to the use of photographic plates for spectrum photography beyond 13,000 Å and reproduced spectrograms to beyond 90,000 Å obtained with its aid: absorption spectrum of liquid methylene chloride showing lines to 21,000 Å; rotation-band spectrum of gaseous hydrochloric acid to 35,000 Å; the absorption band of carbon dioxide at 43,000 Å; water-vapor rotation bands centered about 63,000 Å; and the absorption spectrum of furfural showing bands to beyond 90,000 Å.

By the use of this method, therefore, it is possible to record the infrared out to much longer wavelengths than can be attained by any other method than the use of a purely physical instrument.

In 1945 Swings⁴⁷ published a survey of evaporographic studies and made suggestions for further research. He appeared to be very enthusiastic about the possibilities of the method for direct photography and spectrography in the astronomical field. As alternatives for the collodion membrane, he suggested the study of other membranes which have become important for electron-diffraction and electron-microscopy studies, for example, polyvinyl formal (Formvar) and polystyrene. Further study of the black absorbing layer is also considered necessary, and Swings proposes some which have been used by Pfund for making thermopiles. Study of the infrared absorption and scattering of thin films of metallic black is important. Metallic reflecting coatings prepared by vacuum distillation also might be used, especially as it appears that they have a nearly constant absorption coefficient through the infrared. One drawback to a metallic layer, however, might lie in its thermal conductivity, which would tend to reduce the sharpness of the images.

Swings summarizes the desirable characteristics of the evaporating liquid as follows: it should give a uniform layer and not

an agglomeration of drops; it should have a vapor pressure of the order of 10^{-2} mm; it should be as inert as possible and not attack the membrane or any other part of the apparatus; it should have a sufficiently long life, and not evaporate in a matter of seconds.

A camera for evaporographic studies is a relatively simple affair. It consists essentially of an enclosure that can be evacuated to a pressure of about $\frac{1}{100}$ of a millimeter. On one side there will be a rock-salt window to admit the infrared image and on the other an optically flat glass window through which photographs can be taken by an external camera. Inside the camera is a ring carrying the membrane arranged to have as little contact as possible with the walls and a small electrically heated coil to vaporize the oil. The infrared spectrum to be photographed is focused on the black side of the membrane through the rock-salt window. A parallel beam of light from which orange, red, and infrared has been filtered out is projected normally onto the front of the membrane by a half-silvered mirror, and the light reflected from the membrane is photographed through the mirror, normally to the surface of the membrane. When the membrane is to be prepared for a new oil coating, it is merely exposed to the unfiltered radiation from a lamp in order to evaporate all the remaining oil.

INFRARED PHOTOGRAPHY BY THE PHOSPHOROPHOTOGRAPHIC METHOD

When certain substances are irradiated by short-wavelength ultraviolet or blue light, they glow with a light of a color which is of longer wavelength than that of the exciting light. This glow is known as phosphorescence if it persists for a time after the stimulating radiation is shut off. While it persists, it undergoes a continual decrease in brightness, that is, it "decays," rapidly at first and progressively slower (apparently exponentially). It possesses an interesting property in that it is rapidly extinguished if exposed to infrared radiation. This action appears to have been known to Ritter⁸⁴ and Seebeck⁸⁵ in the early years of last century and was mentioned by Goethe⁸⁶ in his "Farbenlehre." It was first seriously studied by the French physicist

E. Becquerel ⁵¹⁻⁵³ about 1842. Becquerel does not appear to have known of the work of the two investigators first mentioned.

The materials which have been most studied in this connection are calcium sulphide (Balmain's paint), zinc sulphide (Sidot blende), cadmium sulphide, alkaline earth sulphides, and zinc silicate (Willemite). If a phosphorescent substance, such as Balmain's paint or powdered zinc sulphide, is spread in a thin layer on a sheet of glass, or pressed into a plastic material such as celluloid, it will give a glowing layer when exposed to the light of a carbon arc or a mercury lamp. If such a glowing sheet is exposed to the spectrum, the phosphorescent glow will be extinguished by the spectral lines in the infrared, and they will appear as dark on the light background. In most cases, depending on the nature of the material and the wavelength and time of action of the infrared radiation, there will be first of all an increase in the brightness of the glow, followed by a rapid decrease. The final effect in all cases, however, is an extinction of the phosphorescence in the parts exposed to the infrared in a time in which the background glow has not changed much.

It will be clear that we have here a method by which the infrared spectrum may be made visible. By its means Becquerel claimed to have recorded it out to 13,000 Å, using a layer of zinc sulphide. This method of recording the invisible spectrum has been called the "phosphorographic" method.

If a layer carrying this visible record is placed in contact with a photographic plate which is sensitive to the phosphorescent light, it should be possible to obtain a permanent photographic record of the infrared spectrum, the lines appearing light on a dark background. This was first recognized by Draper ⁶⁴ in 1881, and the method which combines the phosphorographic principle with photography has been called the "phosphorographic" method. Using the plates which were available at that time, sensitive only to blue light, and the blue phosphorescing Balmain's paint as the luminous layer, Draper succeeded in photographing the infrared to a wavelength of about 10,000 Å. In 1890 by the same method, Lommel ^{76, 77} and Fomm investigated the spectrum of the sun out to 9,800 Å.

As soon as color-sensitive photographic plates became available, it was possible to use materials such as zinc sulphide which

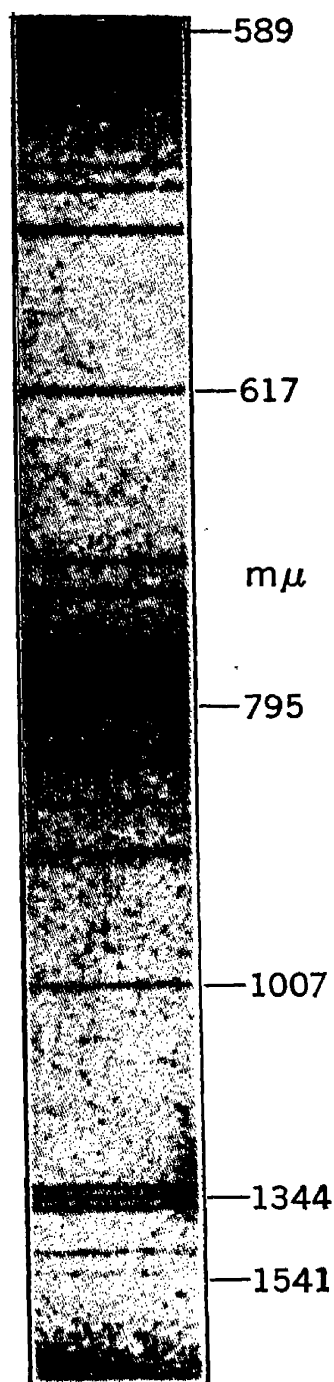


FIG. 23. Infrared phosphorograph of the spectrum of rubidium, showing a line at 15,410 Å (made by Lehmann, copied from Wolf-Czapek⁵⁸).

phosphoresce in the green. With orthochromatic plates, Dahms⁶³ in 1903 gave 13,000 Å as the limit in the infrared which could be recorded using zinc sulphide. Three years later Lehmann⁷¹ used an infrared spectrograph of high aperture and specially optically corrected for the infrared, and placed the limit which could be recorded by the use of zinc sulphide at about 20,000 Å. Lehmann's method was to prepare a layer of finely powdered zinc sulphide and to excite it to phosphorescence by exposure to blue light for one-quarter to one-half minute. It was then exposed in the spectrograph for 1 to 2 minutes, immediately placed in contact with a green-sensitive photographic plate for a time ranging up to 2 hours, and then developed. In Figure 23 is reproduced a photograph of the infrared spectrum of rubidium showing a line at 15,410 Å, taken in this way by Lehmann.

In 1908 Bergmann,⁶⁰ in Lehmann's laboratory, described the results of a study of the emission spectra of the alkali metals, made by means of the phosphorographic method. He used a spectrograph which employed the lens calculated by Lehmann⁷¹ to record the spectrum out to about 20,000 Å. The phosphorescent plate was of zinc sulphide, and the photographic plates were sensitive to the green. The phosphorescent plate was excited by exposure to diffuse daylight or to the light from a carbon arc passed by a blue filter of copper ammonium sulphate. In this way he was able to record many lines out to about 15,400 Å.

Geiger⁶⁵ in 1912 described some attempts to record the spectrum of the iron arc in the near infrared using the phosphorographic method; these failed because he used a Rowland plane grating in his

spectrograph, and the intensity of his spectrum was too low. Bergmann and others who were successful used a prism spectrograph. Geiger described an interesting arrangement in the plateholder of his spectrograph, whereby he could expose one photographic plate repeatedly to the phosphorogram.

In 1914 Ignatieff⁶⁹ published the results of measurements he had made by the phosphorographic method to determine the wavelengths of the helium line at 10,830 Å and the cadmium line at 10,394 Å by the interference method. Takamine and Suga⁸⁷ in 1929 described the measurement by the same method of the helium line at 10,840 Å and mercury lines at 10,114, 11,600, 12,390, and 13,940 Å. With the zinc sulphide screen which they employed, they were unable to obtain records beyond about 17,000 Å. They pointed out that there is a narrow region near 11,000 Å where the power of infrared to destroy phosphorescence is a minimum, so that the phosphorographic method has a low sensitivity in this region. This accounts for the fact that they, and Lehmann, obtained the mercury line at 10,140 Å as weak, whereas energy measurements show it to be the strongest line in the infrared spectrum of mercury.

Much study has been devoted to the quantitative aspects of the growth and extinction of phosphorescence, particularly by Lenard and his school;⁷² Dahms;⁶³ Nichols and Merritt;⁷⁸ Guntz;⁶⁶ Lewschin, Antonow-Romanowsky, and Tumerman;⁷³⁻⁷⁵ Blake;⁶¹ and others. Of particular interest are the studies of the rate of extinction in relation to the wavelength of the extinguishing radiation, the limiting wavelength which is effective, and the laws governing the rate of extinction.

That the action of the infrared depends on its wavelength was recognized in 1876 by E. Becquerel⁵¹⁻⁵³ and later by his son, H. Becquerel,⁵⁴⁻⁵⁸ and was specially studied by Nichols and Merritt.⁷⁸ By using a zinc sulphide in which the wavelength of maximum intensity of phosphorescence was at 5,120 Å, they found that extinction was most rapid with wavelengths in the infrared at 9,000 Å and 13,700 Å. They discovered that there was little action beyond about 15,000 Å, which agrees with the observations of Becquerel⁵⁴⁻⁵⁸ and Dahms.⁶³ Guntz⁶⁶ found a limit at about 16,000 Å. In the experiments of Lehmann,⁷¹ the limit appeared

to be about 20,000 Å. For calcium sulphide it appears to be at about 17,000 to 18,000 Å.

In Figure 24 there is a typical decay curve for a phosphorescent layer, together with a curve showing the rate of decay after

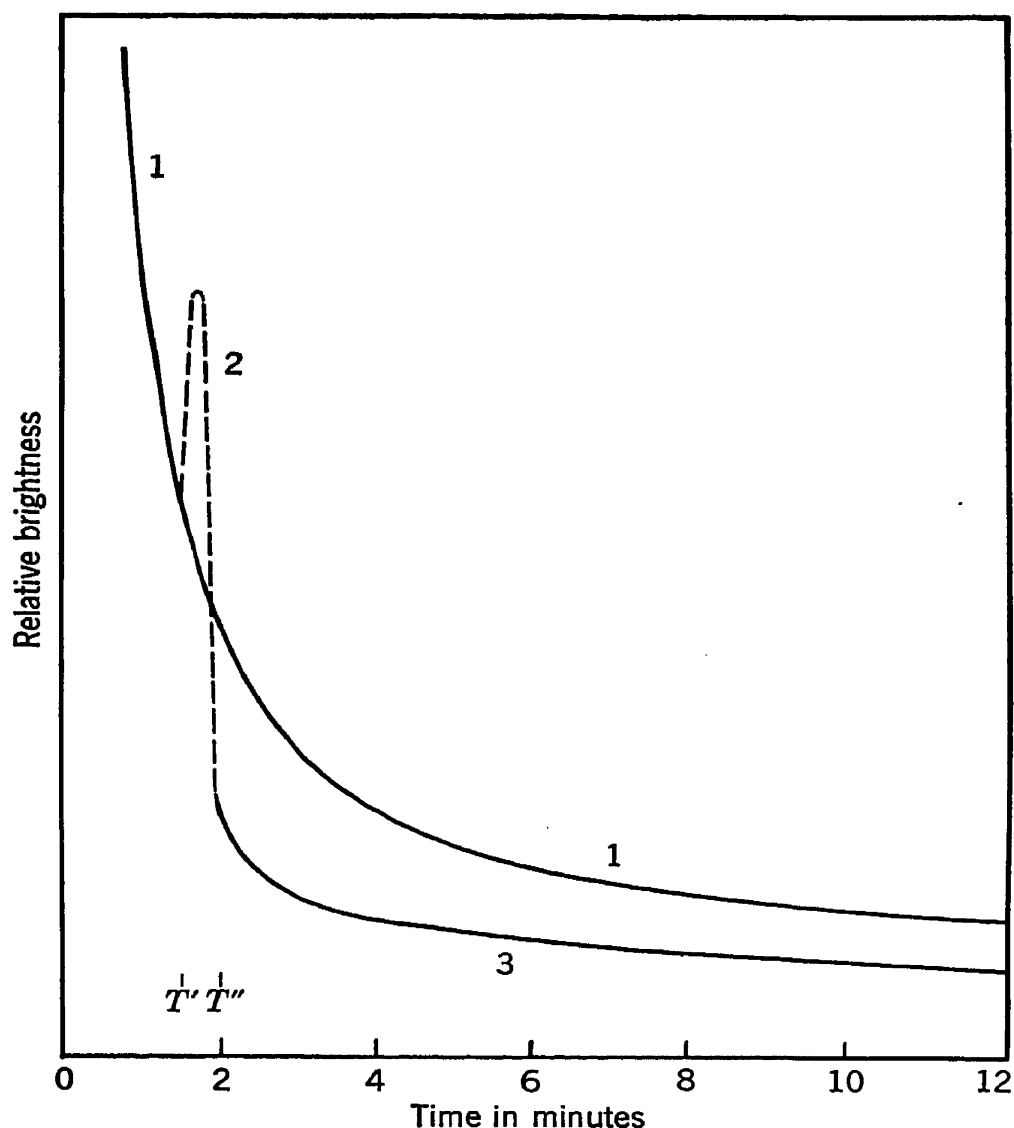


FIG. 24. 1. Typical curve of decay of phosphorescence. 2. Typical curve showing result of exposing the same phosphor to infrared for 30 seconds (T' to T''). The full curves were measured. The dotted curve is qualitative since the brightness changed too rapidly to be measured accurately.

exposure for 30 seconds to infrared quenching radiation. The full-line parts of the curves were actually measured, while the dotted curve is drawn to represent what happens qualitatively in a region where the brightness is changing too fast to be measured accurately. Figure 25 is a typical curve showing the

quenching effectiveness of different wavelengths, made on the same phosphor. It may be seen that the infrared at about 9,500 Å is the most effective under the conditions used. The optimum wavelength band for exciting the phosphorescence of this material was between 4,000 and 4,600 Å. Both curves were measured by E. E. Richardson in the Kodak Research Labora-

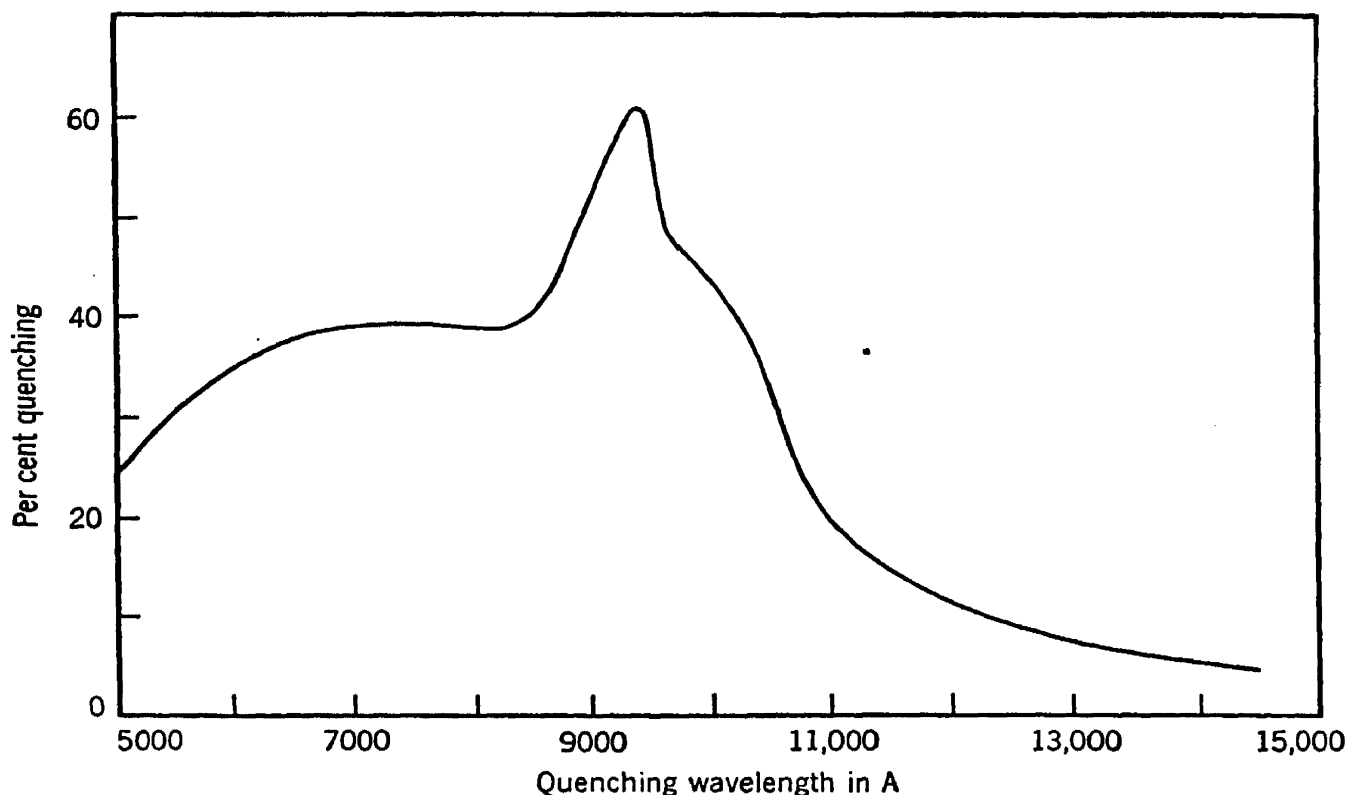


FIG. 25. Typical curve showing extinction effectiveness of different wavelengths, when the same phosphor is used as in Figure 24.

tories, using a blue phosphorescing material, calcium sulphide.

The intensity of phosphorescence depends not only on the way in which the material is prepared but also on the intensity and duration of excitation, the temperature, and the previous history of the material. There may be some semipermanent change produced by excitation which may persist for some time after visible phosphorescence has ceased. Nichols and Merritt⁷⁸ found that in the case of Sidot blende this condition may be destroyed and the layer restored to a standard state by a brief exposure to red or infrared rays. The rate of extinction of phosphorescence by infrared depends on a variety of factors, including the infrared wavelength, the temperature, and the intensity and duration of

the exciting exposure and of the infrared exposure. Blake showed that, if a phosphorograph is produced on a phosphorescent plate, it may be "frozen in" by lowering the temperature, and that it will return unimpaired if the plate is restored to its original temperature.

The success of the phosphorographic method depends on the selection of the optimum relation between the conditions of excitation and extinction, and the best values should be determined by varying the conditions. The problem has been studied by many people, notably by Lewschin, Antonow-Romanowsky, and Tumerman.⁷⁵ They found that the extinguishing effect of a certain quantity of infrared was independent of the intensity and time of exposure to it, provided the product of the two was constant. In other words, the Bunsen-Roscoe reciprocity law holds. For different wavelengths of infrared the same relation holds, although the effect varies in intensity according to the wavelength. It was also shown that the curve obtained by plotting the decrease in density due to exposure to phosphorescent layers partially quenched by infrared of intensity I , as a function of I , resembles the normal characteristic curve of a photographic film.

Photographs have been made in a normal camera by illuminating the subject by a high intensity of infrared, as from a high-wattage spot light, and "photographing" it on an excited phosphorescent plate. A phosphorescent negative is obtained by extinction and can be printed by contact on a sheet of film or paper. There is naturally a limit to the exposures, possibly owing to the rate of decay of the glowing plate, and the photographic image will be coarse and grainy owing to the granularity of the phosphorescent layer. Moreover, the method is not so satisfactory as the straightforward photographic method in the spectral region for which plates or films are available. In all this work, it is clearly desirable to select a film which responds to the light emitted by the glowing plate, and, where the record is being transferred by contact, the contact must be very good, or definition and resolution will suffer.

Instead of the luminous record being transferred by contact to the film, it can be photographed. It has been proposed that the distribution of temperature at the surface of a hot body be determined in this manner. An image of the surface is projected

onto an excited phosphorescent screen, the glow is extinguished to an extent depending on the temperature, and the screen is copied.

During World War II many new phosphors were produced. One of them used for photographing spectra to 15,000 Å can store up energy after excitation by ultraviolet and release it as phosphorescence on later exposure to infrared.^{78a}

USE OF THE ELECTRON-IMAGE TUBE

Another indirect method of infrared photography, worked out by Zworykin and Morton,^{102, 103} involves the application of electron optics in the so-called electron-image tube. This consists of a cathode which is so sensitized that it will give off electrons when illuminated by ultraviolet, visible, or infrared radiation; a fluorescent screen; and an electron optical system to focus on the screen the electrons from the cathode (see bibliography, p. 130).

If an image is projected on the cathode, electrons will be emitted from its surface in proportion to the illumination at any point. Close to the cathode, therefore, the electrons leaving it form an electric image which is a reproduction of the light image. By electrostatic means, the electrons can be accelerated to a high velocity and brought to a focus at the point at which they strike the fluorescent screen. The electrons falling on the screen excite it to fluorescence, and so a visible image is seen on the screen and may be photographed.

The nature of the material used in preparing the photosensitive cathode will depend upon the spectral region in which high sensitivity is desired. If the image projected upon it is of infrared radiation, a cathode sensitized with caesium on silver oxide is used. This layer is made very thin so that electrons will be emitted from the face of the cathode inside the tube when an infrared image is projected upon the outside of the tube.

The most interesting part of the electron-image tube is the means for focusing the electrons on the fluorescent screen. For a detailed discussion of this the reader should refer to the literature (see p. 130). It is sufficient to say here that the focusing of the electrons is effected by means of electrostatic fields which form what can be called an "electron lens," which treats electrons

in a manner similar to that in which an optical lens treats a beam of light.¹⁰³ The image produced by the electron lens resembles that produced by a thick glass lens in that it is inverted, the field is curved, and the image shows pincushion distortion. These defects can be corrected by suitable electrical means, and, moreover, the focal length of the lens can be varied electrically.

The electron-image tube has been applied to infrared photomicrography. The object on the microscope stage is illuminated by infrared radiation, and its image is projected by the microscope on to the cathode of the tube. A visible image of the object appears on the fluorescent screen on the other end of the tube. It can be observed there visually, or, if a permanent record is desired, the image on the screen can be photographed on a film sensitive to the visible light which the screen emits.

In addition to its use in photomicrography, the electron-image tube has been applied to the telescope. This makes it possible for one to see distant objects illuminated by infrared and to study the penetration of haze and smoke by infrared, as well as to signal and see in the dark by invisible infrared rays. In these cases also, the image on the screen may be photographed if a permanent record is desired. Since the brightness of the image obtained is determined by the characteristics of the fluorescent screen and the electric circuits, there is no reason why it should not be possible to make it brighter than the original subject, a result impossible to achieve in the optics of light.

The tubes available for general use at the time of writing this book will not respond to infrared of wavelength longer than can be photographed. Much work has been done, however, for military purposes, and presumably infrared instruments of greater sensitivity further in the infrared will eventually be available.

In addition to the electron microscope and telescope, various devices have been described for viewing and examining materials by infrared. Ybarrondo,¹⁰⁴ for instance, passed infrared rays through photographic film and received the transmitted radiation upon an infrared-sensitive device, in order to ascertain the degree of development of the film, to determine the printing exposure for a negative, and to test the thickness of emulsion coating of unexposed film. In this last instance, infrared is used in order to avoid fogging of the film, which would result if visible light were

used. Earlier inventors had proposed red light for the purpose and the use of selenium cells in determining printing exposures, but without confining the radiation to the infrared. Siemens and Halske¹⁰⁰ proposed that infrared be used in the examination of materials, such as photographic films, which are spoiled by visible light. The infrared image of the object being examined is converted into a visible image by a television device, using screens which change color or develop color on exposure to heat rays, phosphorescence quenching, and so on. Clearly, the visible image could be photographed if a permanent record were required.

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Chapter VII

SOURCES OF INFRARED RADIATION

Whatever the nature of his work, the photographer desires to make his pictures with light of the right spectral quality, with the shortest attainable exposure and the minimum consumption of electricity. There are problems, therefore, for both the photographic manufacturer and the lamp maker. The former aims to make his films very sensitive in the desired spectral region, whereas the latter strives to make sources which shall have as much energy as possible in this region, coupled with the minimum utilization of electric power. In another part of this book we have considered the characteristics of the photographic material. In this chapter, attention will be devoted to the properties of various sources with special reference to their infrared radiation. It is believed that this knowledge will be of benefit to the photographer and will enable him to make the most judicious selection of sources for various classes of infrared work.

The best-known source of light is the sun. It gives life and health and is a most efficient means of illumination. In the practical utilization of sunlight, however, a number of inconveniences are encountered. It cannot be switched on and off at will. It cannot be carried around to illuminate dark corners. It cannot be used at all at night time, except indirectly by the poor light of the moon which reflects it. Moreover, it is very fickle in its behavior even during the day, changing in its intensity and color according to the hour, the season of the year, and the part of the earth on which it shines. Clouds and fog may obscure it at most inconvenient times.

From the dawn of civilization, man has needed some artificial source of light which he could produce at will to lighten the darkness which fell when the sun withdrew. Primitive man invented the fire drill for producing flame, and, while still a dweller in the caves, he found that fats and oils would burn, giving him both

heat and light. He discovered the torch, which led to the invention of the wick, the early oil lamp, and the candle. In 1802 Murdoch in England used coal gas for illuminating a factory, and in 1810 the Gas-Light and Coke Company was formed to light the streets of London with gas. At about the same time, Humphry Davy showed an arc light between carbon poles in the theater of the Royal Institution. Thirty years later, Faraday invented the principle of the dynamo, in which electric current could be produced by mechanical machines. In 1847 Grove lit the London Institution with small electric lamps having filaments of platinum. The carbon-filament lamps of Swan and Edison, during the second half of last century, were the forerunners of the electric lamps of today. The problem of bringing light into darkness at the will of man is solved. The chief concern of the lamp maker at the present time is to find a method of increasing the luminous efficiency of his products.

It is characteristic of all these sources of light that they are hot. Whether they are produced by flames or electric current, the thing which is primarily produced is heat, and, if the bodies are hot enough, there is light accompanying the heat. The emission of the light is the result of "incandescence," defined by Silvanus P. Thompson⁵⁸ as "the shining of hot bodies because they are hot." The incandescent-light sources provide one of the great classes of illuminants. Because they are the result of the heating of materials, they are also good sources of infrared. If a poker is put into the fire and warmed, it may give the sensation of heat without emitting any light. If it is left longer in the fire, it will become red hot, giving off light as well as heat. On still longer heating it may assume an orange color, and if it is melted in a furnace the molten iron will be whitish in color. The hotter a body becomes, the whiter is the light it gives off.

All sources of incandescent light, whether the sun, oil lamps, gas burners, candles, or electric-filament lamps, depend for their light on the heating of matter, either as the result of the combustion of gases or the passage of an electric current. The candle flame, in which the light is due to the heating of tiny particles of carbon at relatively low temperatures, is yellowish in color. The ordinary electric lamp is whiter, because its metal filament

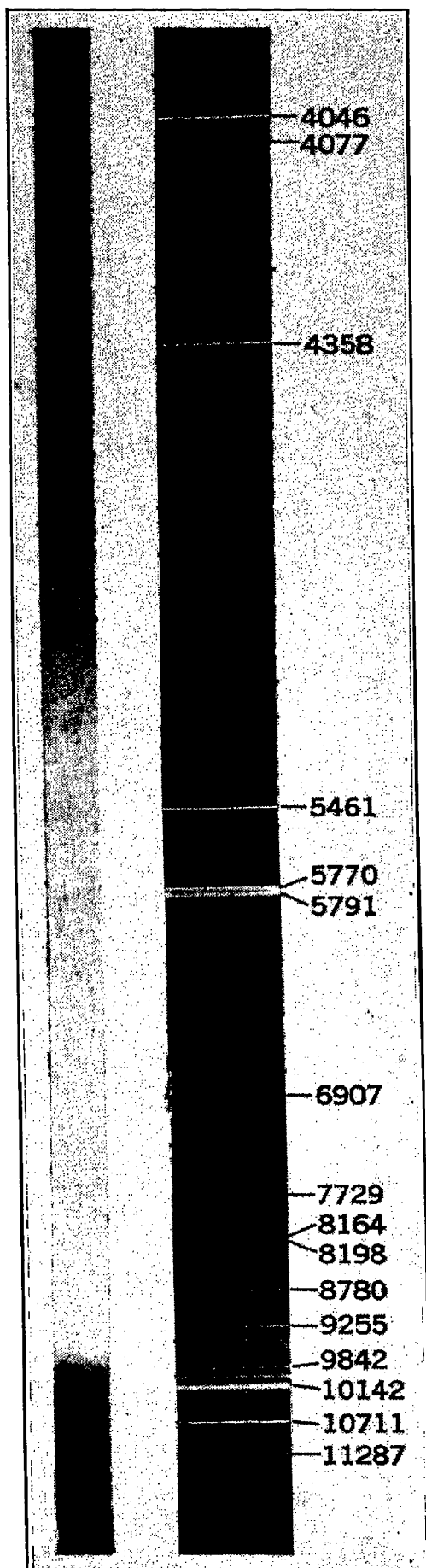
is hotter. The light from the hotter electric arc is still whiter, while the sun, the hottest body known, gives the whitest light.

No incandescent lamp is known in which there is no infrared and heat accompanying the light. This is an inconvenience to the illuminating engineer who would like to have a lamp which is so efficient that it emits nothing but light. To the photographer in the infrared, however, it is a great convenience, because it means that every source of incandescent light is a source of infrared. Naturally, various lamps differ in their effectiveness for infrared photography, and in the course of this chapter these differences will be pointed out, and attention will be drawn to the sources of infrared most suited for different purposes of infrared photography.

We have mentioned that the incandescent lamps provide one of the two great classes of illuminant. The other class includes those which are known as "luminescent" sources, in which the production of light is not the result of the heating of matter. Examples of this are the firefly, luminous fungi, phosphorescent screens, the mercury-vapor lamp, and other discharge lamps. Consideration of the characteristics of these sources is left until later. The incandescent sources are considered first.

In the study of the characteristics of light sources, it is desirable to know the intensity of radiation which they emit at various wavelengths, in particular, in the part of the spectrum used in making photographs. It has already been shown how the light from a source may be split up into its spectrum, giving a band of increasing wavelengths which passes from the ultraviolet, through the visible colors, and into the invisible infrared. All light sources give such a spectrum, the character of which varies with the nature of the source. In fact, there are two types of spectrum: continuous spectra which are uniform and show no interruptions; and discontinuous, or line or band spectra, which are characterized by series of separated lines or narrow bands. Sometimes the lines and bands will be superimposed on a weaker continuous background. Typical line and continuous spectra are shown in Figure 26.

Light and heat are forms of energy. The intensity of radiation emitted by lamps at different wavelengths is usually represented



by so-called spectral-energy-distribution curves, in which the energy at each wavelength is plotted against the wavelength. The energy is measured in the ways known to physicists, by the use of such instruments as the photometer, radiometer, bolometer, or by photographic means. Energy-distribution curves obtained in this manner are used in this chapter to designate the characteristics of sources of light and infrared. A typical curve, shown in Figure 27, represents the energy distribution from an ordinary 1,000-watt 115-volt incandescent tungsten-filament electric lamp. The amount of energy at any wavelength is denoted by the height of the curve at that wavelength. It may be seen that the energy in the ultraviolet is very low. It increases in the visible part of the spectrum towards the red and reaches a maximum in the near infrared at about 9,000 Å. Beyond that point it gets less as the wavelengths get longer, but there is still an appreciable amount of energy at 25,000 Å. On the figure are marked the ultraviolet, the visible, and the photographed infrared regions of the spectrum. It will be clear that, although the lamp has a very high intensity to the eye, it is still higher in the region of the infrared which can be photographed. Such a lamp, there-

FIG. 26. Typical line and continuous spectra. The line spectrum is from a low-intensity mercury-arc lamp, whereas the continuous spectrum is that from an incandescent tungsten-filament electric lamp.

fore, should be a very satisfactory source of radiation for infrared photography, and practice shows this to be the case. If the significance of Figure 27 is grasped, it will facilitate an understanding of the rest of this chapter, where frequent reference is made to similar curves for other sources.

In the measurement of the spectral distribution of radiant energy, it is customary to express this energy in the form of

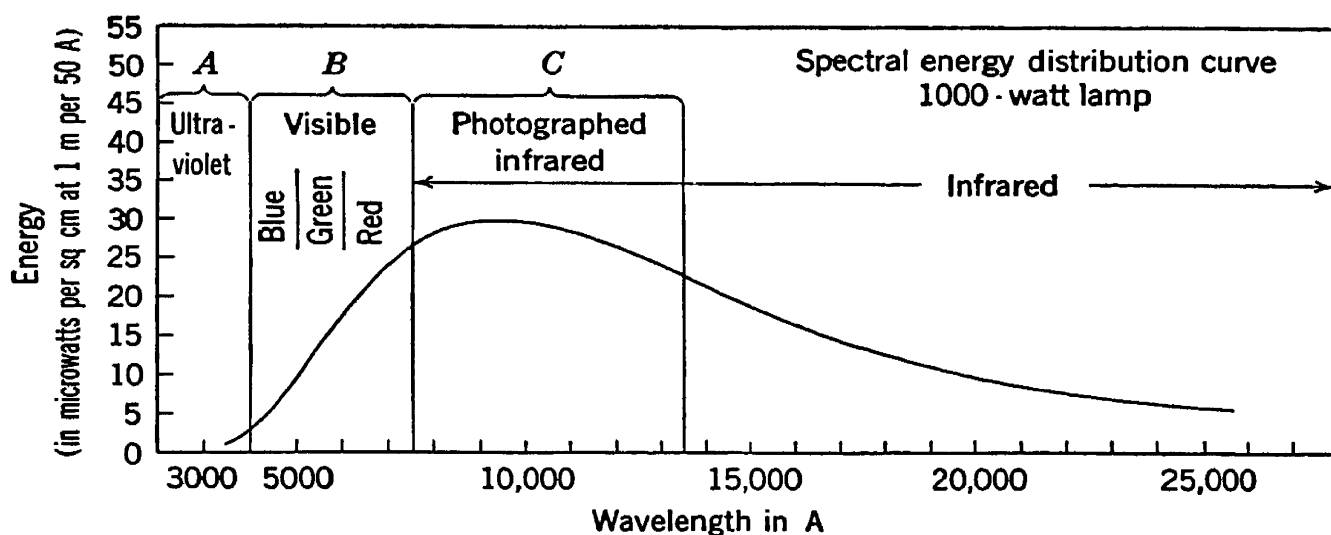


FIG. 27. Spectral-energy-distribution curve for a 1,000-watt incandescent-filament electric lamp.

radiant power in watts or microwatts. When radiant energy falls on a surface, the surface is said to be irradiated, and the rate at which the energy falls on the surface is expressed in power units, for example, watts per square centimeter. When the measurements are made, the spectrum is split up into narrow bands of wavelength, and the power is measured in each band by some suitable means. It is usual to refer all measurements to a band of wavelengths 1 micron (μ) wide. The irradiation then will be expressed, for example, in watts per square centimeter per micron. If any of the units are changed, the value of the irradiation will be changed in proportion. Thus, if the values are expressed in microwatts per square centimeter per 50 Å, the figure must be divided by 5,000 to convert it to watts per square centimeter per 1 μ . (1 watt = 1,000,000 microwatts, and 1 μ = 200 times 50 Å; the factor is, therefore, 1,000,000/200 = 5,000.) In the case of artificial sources it is also customary to include the dis-

tance of the source from the irradiated surface. For example, in Figure 27, the irradiation is given in microwatts per square centimeter at 1 m per 50 Å.

SOURCES OF RADIATION

It has already been stated that sources of radiation can be divided into two classes, one of which includes those which emit spectra that are continuous, whereas the other comprises the sources whose spectra are discontinuous and generally in the form of discrete lines or bands. The boundary between the groups is not sharp, because some spectra are continuous with lines superimposed. It will be convenient here, however, to maintain this subdivision into the two groups, including in the continuous class those sources which emit a relatively bright continuous background on which lines or bands are superimposed. Table X shows the sources of most interest, grouped according to the nature of the spectra.

TABLE X

SOURCES OF CONTINUOUS AND DISCONTINUOUS SPECTRA

<i>Continuous Spectra</i>	<i>Discontinuous Spectra</i>
Black body	Flame carbon arcs
Sun	Metallic arcs, iron, etc.
Incandescent electric lamps	Mercury arcs
Photoflash lamps	Sodium-vapor lamp
Radiant heaters	Other metallic-vapor lamps
Nernst glower	Neon lamps
Welsbach mantle	Glow-discharge tubes
Hydrocarbon lamps	Bunsen burner with salts
Candle	Sparks
Gas flame	Kodatron lamp
Plain carbon arc	
Enclosed metallic arcs	
Fluorescent lamps	

SOURCES WITH CONTINUOUS SPECTRA

It is characteristic of these sources that they are generally incandescent, and the distribution of energy in their spectra is determined primarily by their temperature. Their characteristics resemble on the whole those of the so-called "black body," and their spectral energy distribution varies with temperature in

somewhat the same manner as that of the black body. Before discussing the various sources of continuous radiation of practical value, it is important to consider briefly the significance of this black body, and the attribute of "color temperature" which is ascribed to practical sources and which is based on a knowledge of the black body.

THE BLACK BODY AND COLOR TEMPERATURE

The laws according to which a hot body emits radiation are very well known to physicists and are described in all the textbooks of physics and illuminating engineering.^{20, 46, 49, 62} The perfect radiator is an ideal black object which absorbs all radiation falling on it and reflects and transmits none. The power of emitting radiation is directly proportional to the power of absorbing it, so that a black object which absorbs all wavelengths completely is the best possible radiator. Actually, no substance is known which is perfectly black in this sense. Even lampblack reflects about 1 per cent. However, it is possible to make sources the radiation from which at a particular temperature is identical with that from an ideal black body at the same temperature. These so-called "black-body radiators" are of no value as sources of light or infrared for visual and photographic purposes, but they are very valuable as standards for the measurement and specification of radiation. If the temperature of a perfect black body is known, the distribution of energy through its spectrum can be described accurately.

In practice, the common sources of light do not have a spectral energy distribution corresponding exactly with that of a black body at the temperature of the source. However, the color of the light emitted by a particular source can usually be matched with the color of a black body at a certain temperature. The source is then said to have a "color temperature," the value of which is the temperature of the black body (in degrees Kelvin) which it matches in color. This concept of color temperature is much used in describing the properties of incandescent-light sources and serves as a very convenient approximate specification of the spectral energy characteristics of the radiation from such sources. As the color temperature of a source increases, its light becomes bluer, and its content of infrared becomes relatively

less.¹¹ The color temperature of some common sources of light are given in Table XI (p. 139). Color temperature applies only to matching in the visible spectrum.

The expression "color temperature" can be applied strictly only to sources where temperature is the cause of the radiation. The spectra from such sources are continuous. It is sometimes applied to other sources, and in these cases it is best referred to as the equivalent color temperature. For example, the blue sky is sometimes said to have a color temperature of 25,000° K. This is actually meaningless, because the blue is due not to temperature but to the scattering of light by the molecules of the air. Similarly, certain kinds of vapor lamps and fluorescent lamps are sometimes said to have color temperatures. The radiation spectra of these lamps are primarily in the form of lines and are due to the discharge of electricity in gases and not to temperature. In the case of the fluorescent lamps there is a background of continuous spectrum due to the fluorescence excited by the ultraviolet of the line spectrum of the discharge. If the color of the light from such sources matches that from a black body at a certain temperature, they may be said to have the equivalent color temperature. This value is of no use in determining the spectral distribution of radiation from such sources.

In practice, the actual temperature of the filament of an electric lamp is not the same as its color temperature, but in many cases the spectral distribution of the energy from it matches very closely that from a black-body radiator at all wavelengths.

THE SUN

The sun is the best-known source of visible and infrared radiation. It has a very high intensity and is suitable for photography by visible and infrared rays. There is much variation, however, in the radiation of the sun which reaches the earth, and this requires that the photographer adapt his exposures to meet these changes.

Kimball³⁹ cites six principal causes of variation in the solar-radiation intensity at the surface of the earth: (1) Variations in the amount of heat energy radiated from the sun; (2) variations in the earth's solar distance; (3) amount of water vapor in the atmosphere (in general, this decreases with latitude, altitude, and

TABLE XI
COLOR TEMPERATURE OF VARIOUS LIGHT SOURCES *

<i>Lamp</i>	<i>Color Temperature, °K</i>
Hefner amyl acetate	1,880
Harcourt pentane	1,920
British standard candle	1,930
Kerosene	2,055
Gas flame, bat's-wing	2,160
Acetylene (Eastman Kodak standard)	2,415
<i>Carbon-Filament Lamps</i>	
50-watt untreated carbon	2,080
50-watt GEM carbon	2,195
<i>Vacuum Tungsten-Filament Lamps</i>	
10-watt	2,390
25-watt	2,493
40-watt	2,504
60-watt	2,509
<i>Gas-Filled Tungsten-Filament Lamps</i>	
40-watt	2,760
100-watt	2,865
500-watt	2,960
1,000-watt	2,990
1,500-watt	3,225
<i>Special Gas-Filled Tungsten-Filament Lamps</i>	
60-watt CX	2,825
250-watt CX	2,950
500-watt CX	3,015
500-watt projection	3,190
900-watt projection, 30-volt, 30-ampere	3,200
Photoflood	3,400
G.E. Mazda 3,200 °K	3,200
<i>Other Sources</i>	
Photoflash lamp, no. 20	3,500
Mazda SM lamp	3,300
Wabash Superflash lamp	4,000
Solid carbon arc	3,780
White-flame carbon arc	5,000
Sunlight, mean noon at Washington	5,400
High-intensity carbon arc (sun arc)	5,500
Overcast sky	6,500
Skylight	12,000-26,000

* These values are obtained mainly from the published works of Forsythe and his collaborators.

distance from the ocean, and increases with temperature); (4) dustiness or haziness of the atmosphere (this is apparently closely related to 3); (5) zenith distance of the sun; * (6) altitude. Generally speaking, in the northern hemisphere the water-vapor content of the atmosphere increases at about the same time of the year as the earth's solar distance increases, so that with the sun at any given zenith distance the solar-radiation intensity is much greater in winter than in summer, and in the early spring months than in the late autumn.

The most careful and comprehensive measurements of the distribution of energy from the sun as received at the earth's surface have been made at the Smithsonian Institution Astrophysical Laboratory.¹ Since there are so many variable factors it is difficult to define a normal or average distribution of sunlight on the earth's surface, although it is possible to obtain an approximate curve which serves as a useful guide. The curve shown in Figure 28 represents the irradiation in watts per square centimeter of horizontal surface as a function of the wavelength, for the sun at zenith on a clear day. For comparison, the curve is included for a 1,000-watt 115-volt lamp, which is shown to a larger scale in Figure 33. The data for the sun were taken from the publications of Abbot,¹ at the Smithsonian Astrophysical Observatory. Those for the lamp were kindly provided by Dr. Forsythe.³ It will be seen that the sun has its maximum energy in the visible region, whereas that of the lamp lies in the near infrared. Actually, there are the so-called Fraunhofer lines in the spectrum of the sun, due to absorption by the incandescent gases in the sun's atmosphere, as well as absorption bands resulting from water, oxygen, and ozone in the atmosphere. These have been omitted in the drawing of the curve.

Very few data are available as to the average distribution of infrared energy from the sun received at the earth's surface. This is due to the large variations in the type of illumination received at different places. Fowle²⁷ in 1935 published the curve shown in Figure 29. It discloses the nature of some of the ab-

* That is, the angle between a line from the sun to the observer and a line from the observer to the zenith or the point in the heavens directly above him.

sorption bands in the infrared caused by constituents of the atmosphere. The region covered in the curve is from about 7,000 to 20,000 Å. The curve was taken at sea level at Washington, D. C., and at the time it was made there was about 2 cm of precipitable water vapor in the path of the sun's beam. (Note

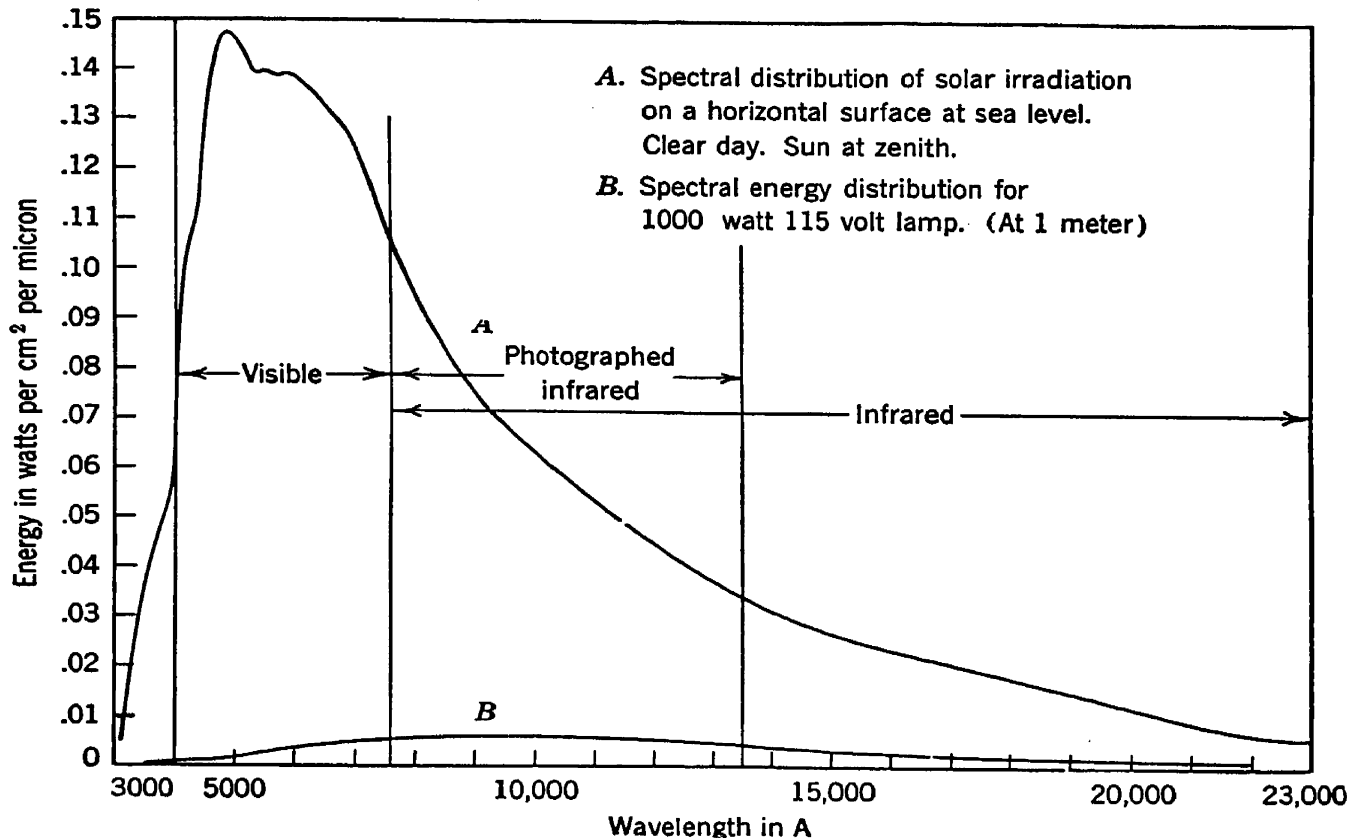


FIG. 28. Spectral distribution of energy from the sun and from an incandescent-filament electric lamp.

- A. Solar irradiation on a horizontal surface at sea level on a clear day with the sun at zenith.
- B. Spectral-energy distribution from a 115-volt 1,000-watt incandescent-filament electric lamp at 1-m distance.

that the wavelength scale closes in towards the longer wavelengths. It is a prismatic scale, equal distances along the spectrum representing greater wavelength regions as the longer wavelengths are approached.) The atmospheric absorption bands are indicated by O and H₂O, indicating oxygen (O₂) and water, respectively. The depth of the water absorption bands depends on the amount of water vapor present in the atmosphere. In fact, the moisture content of the air is sometimes measured by the depth of a band.

During a clear summer day at sea level, the total solar radiation received on a horizontal surface changes, reaching a maximum at noon. As the altitude of the sun varies, so do the spectral character and intensity of the sunlight. Not only do they alter during one day, but also with the season, for the sun attains different altitudes at different times of the year. If a horizontal

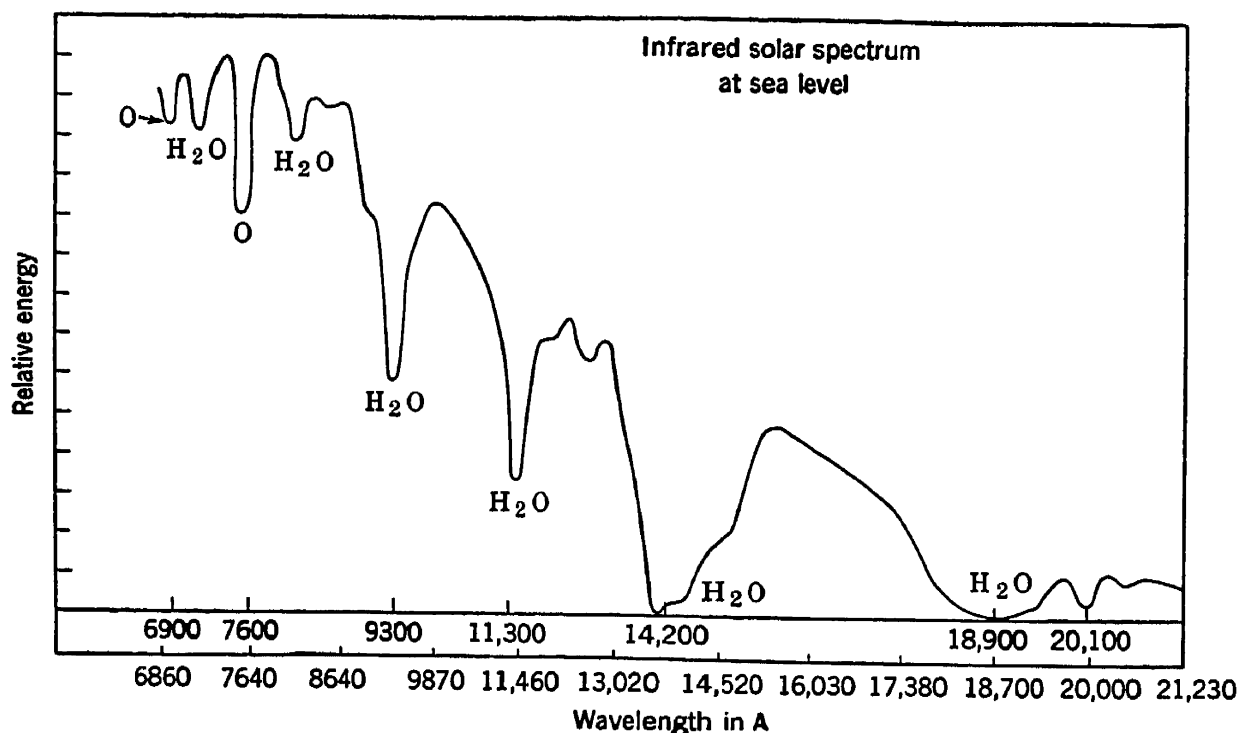


FIG. 29. Infrared solar spectrum at sea level, showing absorption bands due to oxygen (O) and water vapor (H₂O).

(From F. E. Fowle)

card is held out of doors on a sunny day, part of the light which illuminates it comes directly from the sun, while part of it comes from the sky. Figure 30 shows such a record³⁷ of the total radiation from the sun received on a horizontal surface during a day in summer (A), together with the radiation received from the sky (B). At midday, the contribution of the sky radiation in the case shown is about 12.5 per cent of the total. In the middle of the morning and afternoon it is about 20 per cent, whereas near sunrise and sunset it is greater than the direct light from the sun. This is a consequence of the fact that, as the sun approaches the horizon, its direct light has to traverse an increasing thickness of air. If the direct sunlight is measured on a surface which is

continuously changed so that it is always at right angles to the sun's direct rays, the variation is not so great through most of the day as it is when measured on a horizontal surface. The radiation from the sky is strong in ultraviolet and blue, and this

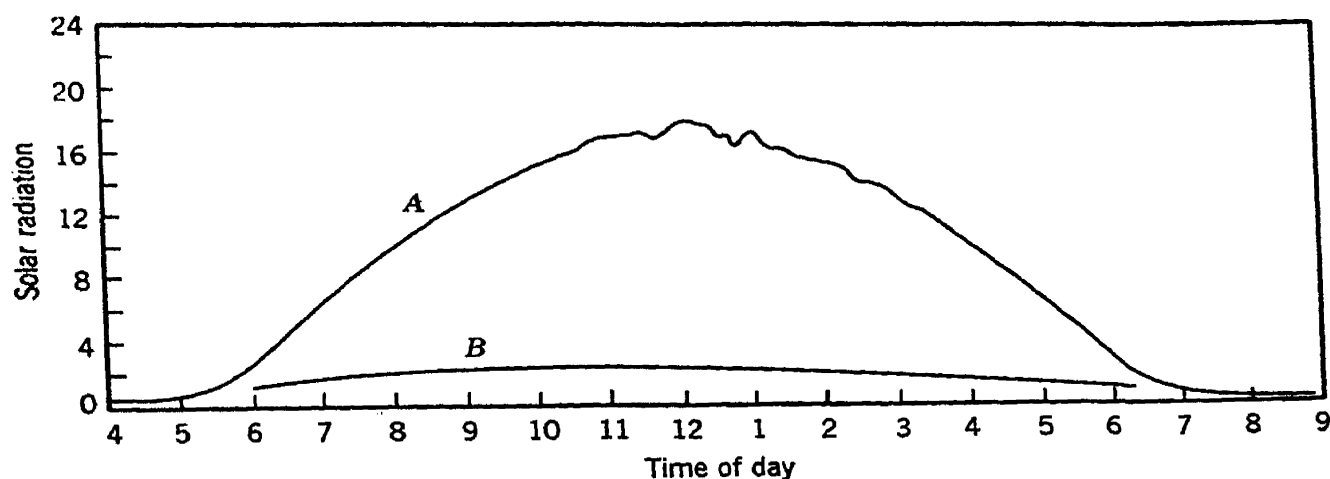


FIG. 30. Comparison of total radiation received on a horizontal surface during a single day from the sun (A) and the sky (B).

(From H. H. Kimball)

modifies somewhat the spectral quality received from direct sunlight alone.

In winter time, the sun attains a lower altitude than in summer, and changes result which resemble those early and late in the day. Further, with the approach of winter, the hours of sunshine decrease to an extent depending on the latitude. Table XII, taken from Luckiesh,⁴⁶ shows the maximum daily duration of sunshine in midsummer and midwinter, for various latitudes.

TABLE XII

MAXIMUM DAILY DURATION OF SUNSHINE

Latitude	December 22	June 21
	(Hours and Minutes)	(Hours and Minutes)
0	12:07	12:07
10	11:32	12:43
20	10:55	13:20
30	10:13	14:05
40	9:19	15:01
50	8:04	16:23
60	5:52	18:52
65	3:34	22:03

As the sun gets lower in the sky, the color of sunlight changes. In particular, the intensity of the short-wavelength ultraviolet and blue radiation diminishes relative to the red and infrared. The maximum in the curve shifts to orange and red, resulting in the well-known yellowing of sunlight late in the day. Figure 31 shows some curves derived by Kimball³⁸ in which the effect of the sun's altitude on the spectral irradiation curve is evident.

Curve 1 is for sunlight outside the earth's atmosphere. Its maximum falls in the blue at about 4,750 Å. Curve 2 was obtained at Calama, Chile, with the sun in the zenith. The curve still has its maximum in the blue, but it is at about 4,850 Å. In curves 3–6, the results are shown for sea level with the sun in the zenith, and at zenith distances 60°, 75.7°, and 80.7°. From curve 3, it will be seen that the absorption by the earth's atmosphere has caused an appreciable change in the curve, particularly in the ultraviolet. The maximum intensity falls in the green at about 5,030 Å. In curves 4, 5, and 6, for the sun at 60°, 75.7°, and 80.7° from the zenith, the change is still more marked, the position of the maximum shifting through the orange to the red. The peaks are at 6,550 Å, 6,900 Å, and 7,200 Å, respectively.

In these curves, allowance is made for scattering by the gases and dust of the atmosphere. They do not show the absorption caused by the great oxygen and water-vapor bands in the infrared beyond 7,000 Å, which are given in Figure 29. For detailed curves, the interested reader should refer to the data of Abbot,¹ and to the curves plotted from them.⁹

Although the spectral quality of sunlight changes with the time of day and the season, the visual color of the light received on a horizontal surface does not change so much as is indicated by the curves in Figure 31. The reason is that the proportion of blue light from the sky increases relatively to the direct sunlight as the sun gets lower in the sky, and so tends to keep the light somewhat bluer. In photographic practice with panchromatic materials, when visible light is used, it is known that towards sunset it is not always necessary to compensate in exposure for any appreciable yellowing of the light.

Of interest in connection with the use of sunlight as a source of radiation for photographic purposes is a knowledge of the energy in different spectral regions. Luckiesh⁴⁶ has published

such data, based on computations by Forsythe and Christison. An extract from his tables is given in Table XIII. The values refer to radiant power, which is the intensity of energy falling in a unit of time on 1 sq cm of area. The data are given in percentages of the total radiation, and as energy values in milliwatts per square centimeter, for a clear day. Three altitudes of the

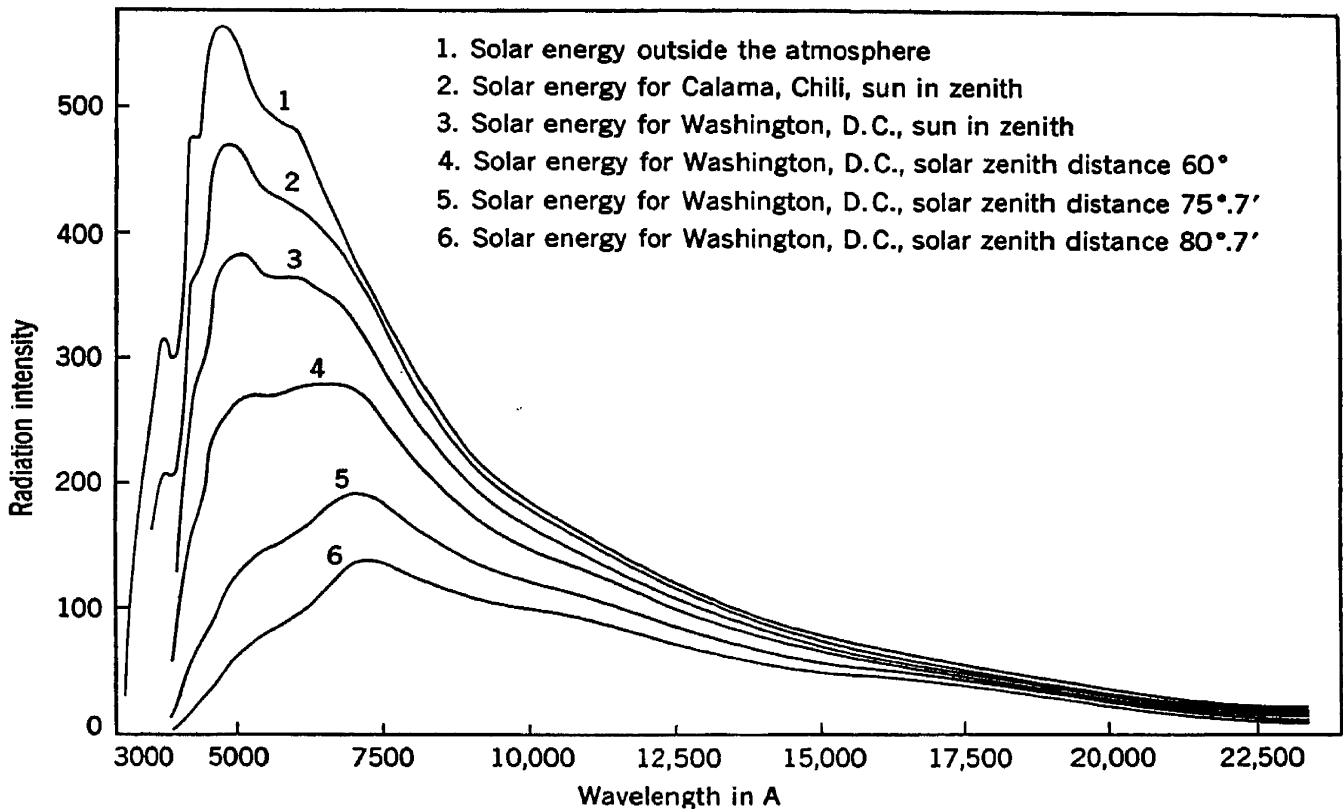


FIG. 31. Effect of the altitude of the sun on the spectral distribution of its energy as received at the surface of the earth.

(From H. H. Kimball)

sun are selected: (1) Sun at zenith, noon, clear day in midsummer; illumination 8,540 foot-candles; this is taken as one standard atmosphere; (2) sun lower, data for February 15, at Cleveland, Ohio; equivalent to 1.5 atmospheres; illumination 4,940 foot-candles; (3) sun still lower, on December 21, at Cleveland, Ohio; equivalent to 2.37 atmospheres; illumination 2,415 foot-candles.

These computations will serve as a general guide to the distribution of the energy of the sun through the spectrum when the sun is at different altitudes. For a standard atmosphere, it will be seen that some 52 per cent of the total solar energy reach-

ing the surface of the earth at noon on a clear day in midsummer is in the infrared. About two thirds of this, or one third of the total energy, is in the region available to infrared photography. It will also be observed that, as the sun declines (both daily and seasonally), the percentage of the sun's radiation which is in the infrared increases from 52 per cent in midsummer to 59 per cent in midwinter. The percentage in the photographic infrared region rises slightly from 35.6 to 38.2 per cent. At the same time,

TABLE XIII

SOLAR-RADIATION INTENSITY IN DIFFERENT SPECTRAL REGIONS

<i>Spectral Range in A</i>	(1) 1 Atmosphere		(2) 1.5 Atmospheres		(3) 2.37 Atmospheres	
	<i>Total Radiation, Per Cent</i>	<i>Milli- watts per Sq Cm</i>	<i>Total Radiation, Per Cent</i>	<i>Milli- watts per Sq Cm</i>	<i>Total Radiation, Per Cent</i>	<i>Milli- watts per Sq Cm</i>
2,900-4,000	3.9	4.22	2.8	2.7	1.62	1.3
4,000-7,600	43.7	46.8	42.1	40.4	39.1	31.4
7,600-14,000	35.6	38.1	37.1	35.7	38.2	30.6
14,000-	16.8	17.9	18.0	17.3	21.1	16.9
Total infrared	52.4	56.0	55.1	53.0	59.3	47.5
Total radiation	100.0	107.0	100.0	96.1	100.0	80.2

the actual infrared energy in the photographic region drops from about 38 to 30, while the total radiation declines from 107 to 80 milliwatts per square centimeter.

As pointed out previously, the variation of moisture content in the atmosphere produces appreciable changes in the strength of the water-absorption bands in the infrared, and thus will affect the proportion of infrared radiation relatively more than the visible. Further, dust, smoke, and other atmospheric impurities will have an effect. The values in Table XIII are for direct sunlight incident perpendicularly on a surface, for a clear day with an average clear atmosphere. Therefore they are to be regarded as close to maximum values, and the factors previously mentioned, the altitude of the sun, and the angle at which the sun's rays strike the measuring surface all will decrease these average maximum values very much.⁴⁶ They are, however, of value as a general guide.

The photographer is interested in knowing whether there is a strict relationship between the intensity of visible sunlight and

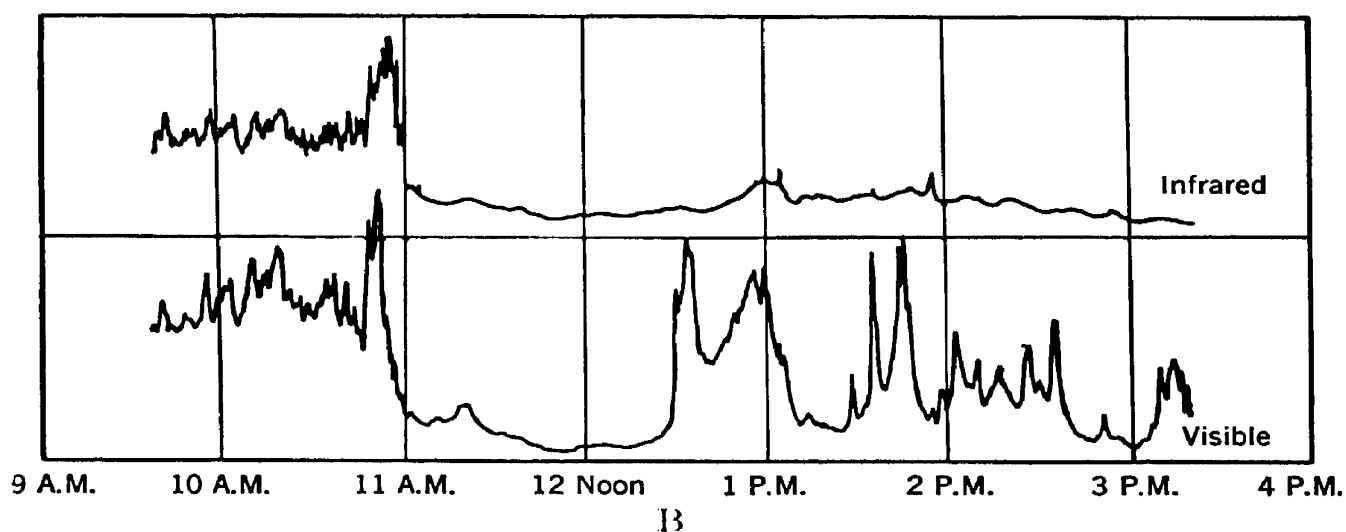
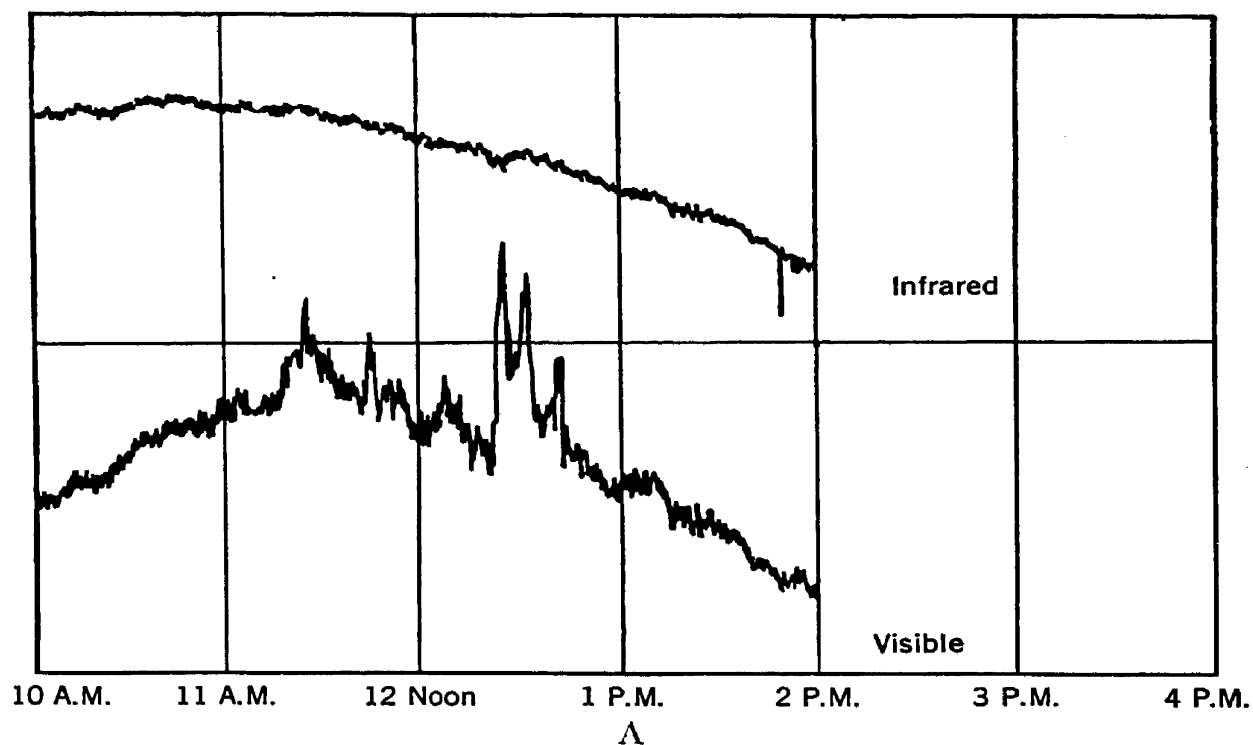


FIG. 32. Infrared and visible content of daylight on two days. The upper curves show the variation in infrared and the lower curves the corresponding variation in visible light throughout the days.

(Courtesy G. B. Harrison and *Photographic Journal*)

that of the invisible infrared. If there is, the use of an exposure meter which gives a value corresponding to the intensity of visible light may be used for determining exposures by infrared. Har-

arrison³⁰ made some observations of interest in this connection, using copper oxide photoelectric cells. The diagrams shown in Figures 32A and 32B are selected from Harrison's results.

The upper curve in each case represents the variation through the day of the infrared part of daylight, whereas the lower curves represent the variation of visible daylight. The curves in Figure 32A were obtained in England on December 7, 1932, when the sky was clear and sunny. In the early part of the day there was some haze through which the sun appeared red. The visible light was somewhat suppressed by the haze, while the infrared penetrated it very well. As the day advanced, the haze disappeared, and the visible light increased, although it may be noticed that there was very little change in the infrared. There were no clouds in the sky all day, and the sharp changes in the intensity of the visible light were caused by variations in the density of mist. These variations caused relatively little corresponding fluctuations in the infrared intensity.

The curves in Figure 32B were obtained on January 23, 1933. The weather varied somewhat. Before 11 o'clock the sun shone fairly brightly, but after this time there were cloudy conditions. At about 12:30 the clouds became much lighter. The large increases in visible intensity are due to the appearance of the sun as a white disk through light cloud. Although the light clouds let through much visible light, they did not transmit very much infrared.

It is clear from this work of Harrison, and from previous considerations discussed in this chapter, that a determination of the intensity of visible light by an exposure meter may lead to serious errors in exposing infrared plates and films. For example, in Figure 32B, between 12:15 and 12:30 P.M., the visible intensity increased by about 16 times, while the increase in infrared intensity was less than doubled. The only satisfactory exposure meter for infrared photography would be one whose sensitivity was confined to the infrared. None of the customarily used photoelectric meters would be satisfactory, since they are not very sensitive in the infrared. Visual meters would be useless. Special infrared meters can be made, but they are usually of low sensitivity, and are therefore of little use without amplifying electric equipment.

It is a common experience among photographers using infrared plates and films that when the sun is obscured by clouds the exposure necessary is proportionally longer than that which would be required with ordinary photographic materials. In dull and cloudy weather, therefore, the exposures for infrared photography must be increased considerably more than is indicated by exposure tables for ordinary materials. Although it is not possible to give precise directions for exposures in cloudy weather, Rawling⁵³ has given a rule which he states works satisfactorily in practice: "For infrared plates on cloudy days it will be better to multiply the normal 'best-weather' exposure by 4, and on dull days to multiply it by 8 or more as required." For normal materials, the corresponding figures are usually given as 2 and 4.

The difference in the spectral quality of sunlight as compared with the light of the blue sky is of importance to the infrared photographer, because direct sunlight is very strong in infrared, while blue skylight is very poor in it. If, therefore, a subject is illuminated only by light from the blue sky, for example, when it is in the shade, the exposures must be much increased. Even when the bulk of the subject is in bright sunlight, the shadows may be illuminated only by the light from the sky. This accounts for the black shadows, lacking in detail, which are characteristic of infrared photographs out of doors.

ARTIFICIAL INCANDESCENT SOURCES

The most convenient artificial light source is the incandescent tungsten-filament lamp, which is commonly used for general illumination purposes. Other well-known sources which emit continuous spectra are the candle, oil lamp, Welsbach gas burner, the Nernst glower, and the carbon-filament lamp. The arc lamps also are much used as sources of light. They emit a continuous spectrum, which usually has a line or band spectrum associated with it. The candle and oil lamp are of such low efficiency that they are not used in photographic practice. Other sources are used for specific purposes.

The incandescent filament electric lamp consists of a thin filament in a glass bulb. When an electric current is passed through the filament, it glows, emitting light and heat. The earliest filament electric lamps, commercialized by Edison in

1879, had a filament of carbon made by heating sewing thread in an airtight crucible. Later, bamboo was used to replace the thread, and this, in turn, gave place to a filament of cellulose squirted through a die, dried, and carbonized. Methods of treating the carbon filaments were devised to increase their efficiency, but about 1906 lamps were introduced having filaments of metal, and these have practically entirely replaced the carbon-filament lamps, particularly for the purposes of illumination. The first metal filament was of osmium, although the first to be used commercially was made of tantalum. Very shortly, however, this was replaced by tungsten, the metal used in the construction of the present type of lamp.

In the manufacture of the earlier metal-filament lamps, the glass bulbs were evacuated so as to give the highest obtainable vacua. Unfortunately, the lamp bulbs blackened in use owing to the evaporation of the metal of the filament, which formed a dark coating on the inside of the bulb. This effect was studied in a series of brilliant researches by Langmuir, and as a result of them he developed the so-called "gas-filled electric lamp." The evaporation of the filament can be reduced very considerably if the bulb of the lamp is filled with the inert gas, nitrogen, at a fairly high pressure. At the present time, all the tungsten-filament lamps of high wattage are filled with inert gas, usually a mixture of argon, 80 per cent, and nitrogen, 20 per cent, and the filament consists of a close spiral of tungsten wire instead of a straight wire. Coiling of the filament tends to reduce its cool-

the output of light from the lamp is most marked with lamps of higher wattage.

The lamps which are used for photography are all of the high-efficiency gas-filled type, for it is desirable to obtain the maximum of illumination with the minimum number of lamps and the least consumption of electricity. In infrared photography we are not directly concerned with the output of visible light, but

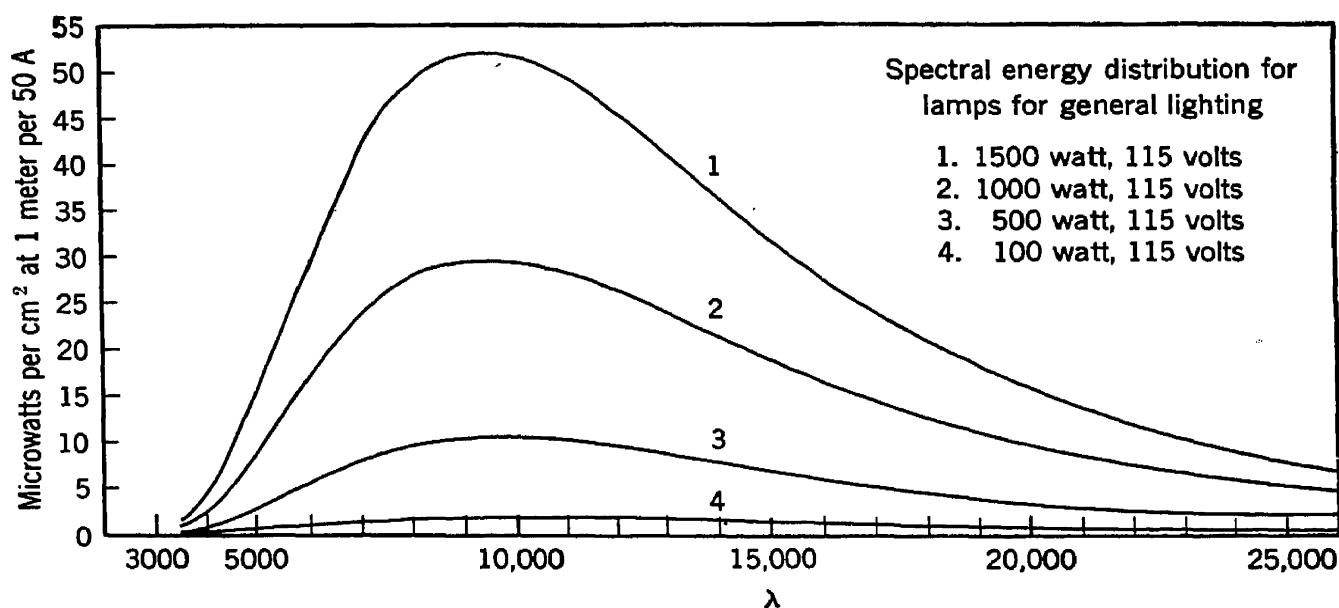


FIG. 33. Spectral-energy distribution for incandescent-filament electric lamps for general lighting purposes.

(Courtesy W. E. Forsythe)

of the infrared between the spectral limits of about 7,000 Å–11,000 Å. It is desirable to select sources which have as great a proportion of their energy as possible in this region. It so happens that the types of lamp most used for illumination and for photography by visible light possess this characteristic. This may be seen by reference to the spectral-energy-distribution curve for a 1,000-watt lamp given in Figure 27. The position of the maximum in the curve is at about 9,000 Å.

The energy-distribution curves for a number of commercially available lamps are shown in Figures 33 and 34, and the data from which they are drawn are given in Tables XIV and XV. They were obtained from information published by Barnes and Forsythe,³ and apply specifically to lamps manufactured by the

Electric Company in the United States.* For lamps of manufacture, see the note on p. 174.

spectral distribution of the energy emitted by lamps of this kind is dependent primarily on the temperature of the filament.⁸ The normal temperature of operation of the filament is determined by the diameter of the wire and the way in which

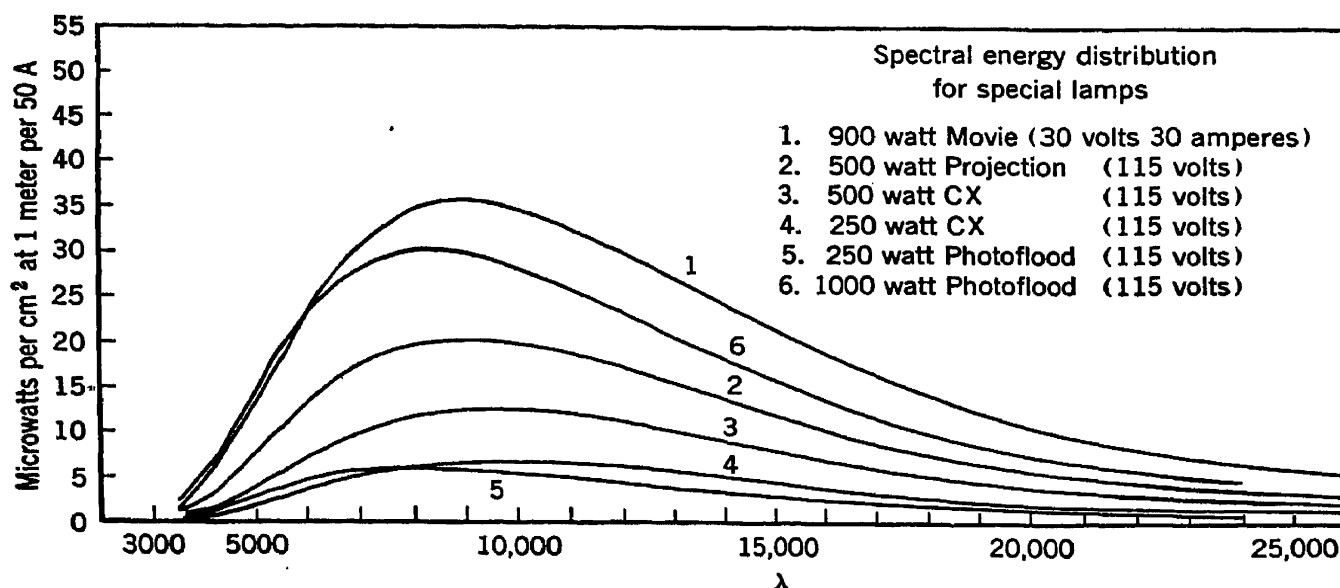


FIG. 34. Spectral-energy distribution for incandescent-filament electric lamps for special purposes.

(Courtesy W. E. Forsythe)

it is coiled and mounted, the gas used in the lamp, and the life for which it is designed. In the case of lamps used for normal purposes of illumination, a long life is desirable, and most lamps for these purposes are designed to give 1,000 hours. The 500-watt lamp for general lighting purposes has a filament that operates at a temperature of 2,940° K, whereas that of the 40-watt lamp operates at a temperature of about 2,710° K. The filament of the 500-watt CX lamp (having an ultraviolet-transmitting glass bulb) operates at the higher temperature of 3,025° K and is designed for a life of about 500 hours. The 500-watt lamp used for the projection of cinematograph films operates at a tem-

*In the case of lamps having the filament in one plane, the energy radiated perpendicular to the plane of the filament was measured; for the other lamps, the radiation perpendicular to the plane of the leads was measured with the leads turned away from and the center of the filament turned towards the spectrometer.

perature of about 3,250° K and has a life of about 100 hours. In the case of the projection of films, efficient production of light

TABLE XIV

SPECTRAL-ENERGY DISTRIBUTION FOR A NUMBER OF LAMPS—115-VOLT FOR GENERAL LIGHTING PURPOSES—MICROWATTS PER CM² AT 1 M PER 50 A *

<i>Wavelength in A</i>	<i>Lamp Watts</i>				
	<i>1,500</i>	<i>1,000</i>	<i>500</i>	<i>100</i>	<i>40</i>
3,500	1.15	0.75	0.225	0.030	0.0075
4,000	4.05	2.22	0.700	0.098	0.0245
4,500	9.0	5.0	1.55	0.238	0.067
5,000	15.5	8.7	2.65	0.435	0.127
5,500	22.2	12.7	3.95	0.66	0.200
6,000	29.7	16.7	5.5	0.89	0.260
6,500	36.0	20.1	6.5	1.12	0.355
7,000	41.5	21.6	7.6	1.31	0.43
7,500	45.5	25.5	8.5	1.47	0.48
8,000	48.5	27.5	9.2	1.60	0.52
8,500	50.5	28.8	9.6	1.70	0.56
9,000	51.5	29.1	10.0	1.75	0.58
9,500	52.0	29.2	10.2	1.80	0.60
10,000	51.8	29.0	10.5	1.81	0.62
10,500	51.0	28.7	10.1	1.82	0.62
11,000	49.8	28.3	9.9	1.78	0.61
12,000	45.7	26.5	9.3	1.69	0.60
13,000	41.5	24.0	8.6	1.57	0.55
14,000	36.8	21.2	7.7	1.43	0.50
15,000	31.8	18.8	6.7	1.28	0.45
16,000	27.5	16.5	5.8	1.14	0.40
17,000	23.9	14.2	5.0	1.00	0.35
18,000	20.8	12.5	4.7	0.87	0.31
19,000	17.9	10.8	3.7	0.76	0.27
20,000	15.5	9.5	3.3	0.66	0.24
22,000	11.6	7.3	2.6	0.52	0.19
24,000	8.7	5.5	2.1	0.39	0.15
26,000	6.5	4.4	1.8	0.31	0.12
Lumens per watt	22.0	20.7	19.6	15.3	10.7
Color temp., °K	3225.0	2990.0	2960.0	2865.0	2760.0

* Data supplied by Dr. W. E. Forsythe.

is more important than a long life, and therefore the filament is operated at a higher temperature than is normal in the case of lamps for general lighting.

TABLE XV

SPECTRAL-ENERGY DISTRIBUTION FOR A NUMBER OF LAMPS FOR SPECIAL PURPOSES—MICROWATTS PER CM² AT 1 M PER 50 A *

Wavelength in A	Lamp Watts and Purpose					
	900 † Movie	500 ‡ Pro- jection	500 ‡ CX	250 ‡ CX	Photoflood	
					250 ‡	1,000 ‡
3,500	1.01	0.56	0.35	0.160	0.45	1.90
4,000	4.1	2.25	1.00	0.48	1.05	4.90
4,500	8.2	4.7	2.2	1.04	1.75	9.30
5,000	13.5	7.5	3.73	1.76	3.05	14.3
5,500	18.8	10.7	5.4	2.52	3.90	19.3
6,000	23.5	13.4	7.1	3.58	4.60	23.0
6,500	27.3	15.6	8.5	4.44	5.10	25.8
7,000	30.4	17.5	9.7	5.07	5.50	28.1
7,500	32.8	18.6	10.7	5.55	5.70	29.4
8,000	34.4	19.5	11.5	5.95	5.75	29.8
8,500	35.2	19.9	12.0	6.25	5.70	29.9
9,000	35.5	20.0	12.3	6.42	5.60	29.6
9,500	35.3	19.9	12.4	6.50	5.40	29.0
10,000	34.6	19.5	12.4	6.52	5.20	28.2
10,500	33.7	19.0	12.2	6.52	5.00	27.0
11,000	32.3	18.5	11.8	6.44	4.70	25.7
12,000	30.0	17.0	11.0	6.12	4.20	23.1
13,000	27.2	15.4	9.9	5.45	3.75	20.5
14,000	24.0	13.6	9.0	4.85	3.25	18.1
15,000	21.0	11.9	7.8	4.33	2.80	15.8
16,000	18.3	10.2	6.8	3.62	2.40	13.6
17,000	16.1	8.4	5.7	3.15	2.05	11.6
18,000	13.8	7.6	5.1	2.74	1.70	9.9
19,000	12.0	6.4	4.3	2.39	1.50	8.4
20,000	10.5	5.5	3.8	2.09	1.30	7.2
22,000	8.7	4.2	2.9	1.63	1.00	5.6
24,000	6.4	3.4	2.2	1.26	0.75	4.6
26,000	5.1	2.8	1.7	1.04	....	....
Lumens per watt	26.5	26.3	21.1	19.0	35.8	31.6
Color temp., °K	3200.0	3190.0	3015.0	2950.0	3440.0	3415.0

* Data supplied by Dr. W. E. Forsythe.

† 30-volt 30-ampere lamp.

‡ 115-volt lamp.

In the development of lamps of the Photoflood and Movieflood types, the General Electric Company sacrificed much of the life of the ordinary type of electric lamp, reducing it to a few hours. In this way it is possible to operate the filament at a considerably higher temperature (over $3,400^{\circ}\text{K}$) and so increase the effectiveness of the lamp both in the visible and infrared. The position of the maximum in the spectral emission curve of the lamp is at shorter wavelengths than for ordinary tungsten lamps of the same wattage. It coincides roughly with the maximum sensitivity of the commonly used fast infrared plates and films, since it is at about $8,000\text{--}8,500\text{ \AA}$.

For a fuller consideration of the characteristics of tungsten-filament lamps, the properties of heated tungsten wires, and the laws of the emission of radiation by heated solids, reference should be made to the articles and textbooks on illuminating engineering and physics listed at the end of this chapter.^{9, 16, 20, 25, 26, 29, 49}

There has long been an idea that the carbon-filament lamp should be a very good source for use in infrared photography, because it is very rich in infrared. Actually, such a lamp has a far higher ratio of infrared to visible light than has the high-efficiency tungsten-filament lamp. Its efficiency is very much less, however, and in the region of the spectrum available for infrared photography the tungsten-filament lamp is far more effective. This can be readily demonstrated by taking two infrared photographs, one with tungsten-filament lamps and the other with carbon-filament lamps, using the same wattage in both cases. It will be found that the exposure with the tungsten-filament lamp will be much less than that required with the carbon lamp.

If a study is made of the curves given in Figures 33 and 34, it will be observed that, as the temperature of the filament increases, the maximum of the energy-distribution curve shifts towards shorter wavelengths. The maximum never enters the visible region of the spectrum, however. Even with the lamps operating at the highest temperature, it lies just outside in the near infrared. Some data concerning the color temperatures of a number of types of lamp are given in Table XI. It will be seen that the carbon-filament lamp operates at a temperature con-

siderably below that of low-wattage tungsten lamps of low efficiency, while the Photoflood type of lamp attains the highest temperature. The maximum in the energy-distribution curve of a carbon lamp lies beyond the photographic limit, while that in the Photoflood type of lamp is at about 8,000–8,500 Å.

It will be clear from the foregoing that for the bulk of infrared photography by artificial light, which is done with plates and films sensitive in the region from 7,000 to 9,000 Å, the Photoflood lamps and the other high-wattage high-efficiency tungsten-filament lamps are very suitable. This is fortunate, because these are the lamps available in photographic studios for ordinary photography.

In general, the glass used in lamps does not have any significant absorption in the infrared region which can be photographed. The General Electric Company of America sells a 250-watt Mazda CX lamp with a special infrared-transmitting glass, Corning no. 254, to confine the transmission mainly to the infrared. Although the glass transmits a certain proportion of visible red light, the lamp has some value in that it eliminates the need for using a filter on the camera lens for infrared photography. The red transmission of the glass, however, is rather too great to permit photography in total darkness. Other lamps are sold in which the clear glass bulb is coated with an infrared-transmitting varnish.

FLASH LAMPS

The photographer has long used various portable devices for producing very bright flashes of light of short duration in places where photographic lighting equipment is not available, or where there is likely to be some tendency for the subject to move. The means employed in the past for achieving this consisted in the use of magnesium in the form of ribbon or foil, and so-called "flash powders," which were made of magnesium powder mixed with other materials, such as potassium chlorate, to increase the rate of burning and to modify the spectral quality of the light. The materials were ignited by a flame or by a spark, a fuse, or an electrically heated wire.

Devices of this nature had a number of disadvantages, among which were a certain inconvenience in preparing the material for

use, the liberation of large quantities of smoke of magnesium oxide accompanying the flash, and an element of danger due to the explosive nature of the materials. At the present time, these drawbacks have been eliminated in a special kind of lamp in which the material causing the flash is enclosed in a glass bulb resembling that of a normal electric lamp. These have been made available commercially under a number of names, such as Photoflash and Superflash lamps, Sashalites, and Photoflux Vacublitz lamps.^{17, 22, 44}

In their early days, lamps of the Photoflash type contained thin aluminum foil in an atmosphere of oxygen. Later, fine wire of aluminum-magnesium alloy was used instead of foil by the Philips and Wabash Companies. The General Electric and Westinghouse Companies later introduced shredded aluminum foil. The amount of wire or shredded foil depends on the size of the bulb, and the lamps are fired by means of a filament covered with a primer which ignites when the filament is heated by an electric current. When it is ignited, the metal burns very quickly, giving a bright flash of a duration of a small fraction of a second.

The region of maximum emission of the Photoflash type of lamp corresponds to the position of maximum sensitivity of the photographic plates and films most used for infrared photography.¹⁷ It is therefore one of the most efficient artificial sources for infrared photography, being surpassed only by certain types of carbon-arc lamp. It is the simplest source to operate, requiring only the battery from an ordinary flashlight.

In an attempt to make a lamp which could be dependably and accurately synchronized with a high-speed shutter, the General Electric Company brought out the SM lamp. It contains no foil or wire, but the flash is produced by ignition of a primer mixture applied to the leads and filament of the lamp in an atmosphere of oxygen. It is operated in the same manner as the Photoflash lamps.

RADIANT HEATERS

The radiant heaters which have been much recommended in the past for therapeutical purposes generally consist of a concave reflector at the focus of which is an incandescent carbon filament in a glass bulb, or a resistance wire embedded in or wound upon

an insulating refractory core, such as steatite or porcelain. The filament heaters enclosed in glass are usually run at a dull red heat and generally emit radiation from about 5,000 to 40,000 Å, with a maximum emission at 11,000–20,000 Å, depending on the temperature of the filament. Glass bulbs used for enclosing filaments do not transmit beyond 40,000 Å.

In the case of the other nonenclosed types of radiant heaters, the emission is also confined almost entirely to the infrared out to about 150,000 Å. The maximum emission shifts according to the temperature. At about 300–400° C it extends from about 40,000 to 50,000 Å, whereas at a dull red heat, 600–800° C it lies between 20,000 and 30,000 Å. At the higher temperatures, the infrared is, of course, more intense than it is at the lower values. A different form of radiant heater, known as the glower rod, has a color temperature which may be as high as 1,800° K. It is a good source of long-wavelength infrared.

Heaters of this type have been stated to be of benefit in therapy. The radiation which they emit, however, is mainly of wavelengths which are fully absorbed at the surface of the skin. They cannot be of value in so-called deep-ray therapy, therefore, and probably act in a purely thermal manner by stimulation of the nerve endings in the skin.⁴⁶ Similarly, they are of no value for infrared photography, since they emit very inefficiently in the spectral region to which photographic plates can be sensitized.

THE NERNST GLOWER

The Nernst glower consists of a small rod of the oxides of certain rare earths heated to incandescence in air by the passage of an electric current through it. The rare earth oxides forming the filament are usually a combination of cerium, thorium, and zirconium oxides, each of which possesses a strong selective emission in the infrared. The Nernst glower provides a very convenient continuous source for the short-wavelength region of the infrared spectrum, and is particularly useful for spectrographic work. It operates very regularly and does not give off products of combustion which may attack apparatus and cause deposits on glass prisms, and the like; it is simple to use and has a high intensity, and the emission is very constant when a constant

voltage is applied. The most important study of the spectral-energy characteristics of the glower is due to Coblentz,¹² who determined the spectral-emission curves at power consumptions ranging from 2 to 123 watts, and to a wavelength of nearly 90,000 Å. With increase in the wattage, the character of the emission changes markedly. The emission spectrum has two main bands at about 15,000–20,000 Å, and at 55,000 Å. At low wattages the latter band is stronger than the former, but, as the wattage is increased, the band at the shorter wavelengths increases in intensity much more rapidly than the long-wavelength band, so that, at the values of wattage at which the lamps are normally operated, the band at 55,000 Å has disappeared almost entirely, leaving the emission confined in effect to the band at 15,000–20,000 Å.

THE WELSBACH MANTLE

The Welsbach mantle, or Auer burner, is well known for its use in the incandescent gas burner which was in vogue before the introduction of the incandescent-filament electric lamp for general lighting. In its most common form it consists of a mantle containing about 99 per cent of thorium oxide and 1 per cent of cerium oxide, heated by a gas flame. It has a strong selective emission in the visible part of the spectrum. It is particularly pronounced in the yellow-green, but has a low emission in the red and near infrared between 7,000 and 50,000 Å. At longer wavelengths, the emissive power is good, and the mantle is much used as a source for the study of the far infrared.^{13, 14, 55, 56} In its normal form, however, it is useless as a source for infrared photography, even in the spectrograph. It is possible to modify the radiating characteristics of the Welsbach mantle so as to increase its emissivity in the near infrared. Barnes and Bonner⁵ achieved this by causing a deposit of carbon to be formed on the mantle by the gas flame. Pfund⁵¹ found that, if a gas flame is allowed to play on the mantle while it is heated by the glow or arc discharge formed between terminals connected to the secondary coil of a high-potential transformer, the performance rivals that of the Nernst lamp in the near infrared from 7,000 to 150,000 Å.

CARBON ARCS

The familiar carbon arc, used for such purposes as studio illumination, projection of films and lantern slides, and therapeutic treatment, is an electric arc formed between two electrodes of carbon. The carbons are in the form of rods connected to a source of electric current, and the arc is struck by putting the tips of the electrodes in contact and immediately separating them by a short distance.

The spectrum of the radiation from the arc consists of a continuous background produced by the incandescent electrodes, and lines or bands due to the vapors. By modifying the composition of the carbons it is possible to vary the characteristics of the radiation so that the spectrum may consist mainly of lines. In fact, arc sources may be classified into two groups according to the nature of their spectra. Spectra which are primarily continuous are given by the so-called "plain" and "neutral-cored" carbons. Lines predominate in the spectra from carbons which are cored or impregnated with salts to give the "flame arcs." The chief source of the radiation of the former is the electrically positive electrode, whereas in the case of the second group it is the luminous flame between the electrodes. The carbon arcs provide the highest available artificial temperature, and color temperatures higher than $5,000^{\circ}\text{K}$ have been obtained.^{15, 43, 46, 49}

In the ordinary plain carbon arc, solid carbon rods are used as the electrodes. When the arc is burning, a crater forms on the positive side, and most of the radiation comes from this. In order to increase the steadiness of the arc, it is sometimes the practice to provide the carbons with cores of certain salts which increase the conduction, but which do not give a marked visible flame. These are the neutral-cored carbons. A modification of the neutral-cored carbon arc designed to give very high brightness is the high-intensity carbon arc. The effectiveness may be increased by rotating the carbons during operation. The color temperature of the plain arc is generally about $3,700^{\circ}\text{K}$, whereas that of the high-intensity arc may be over $5,000^{\circ}\text{K}$. Although the spectra of these arcs are continuous in the manner of other incandescent sources, there is always present a strong emission band at $3,890\text{ \AA}$, known as the cyanogen band.

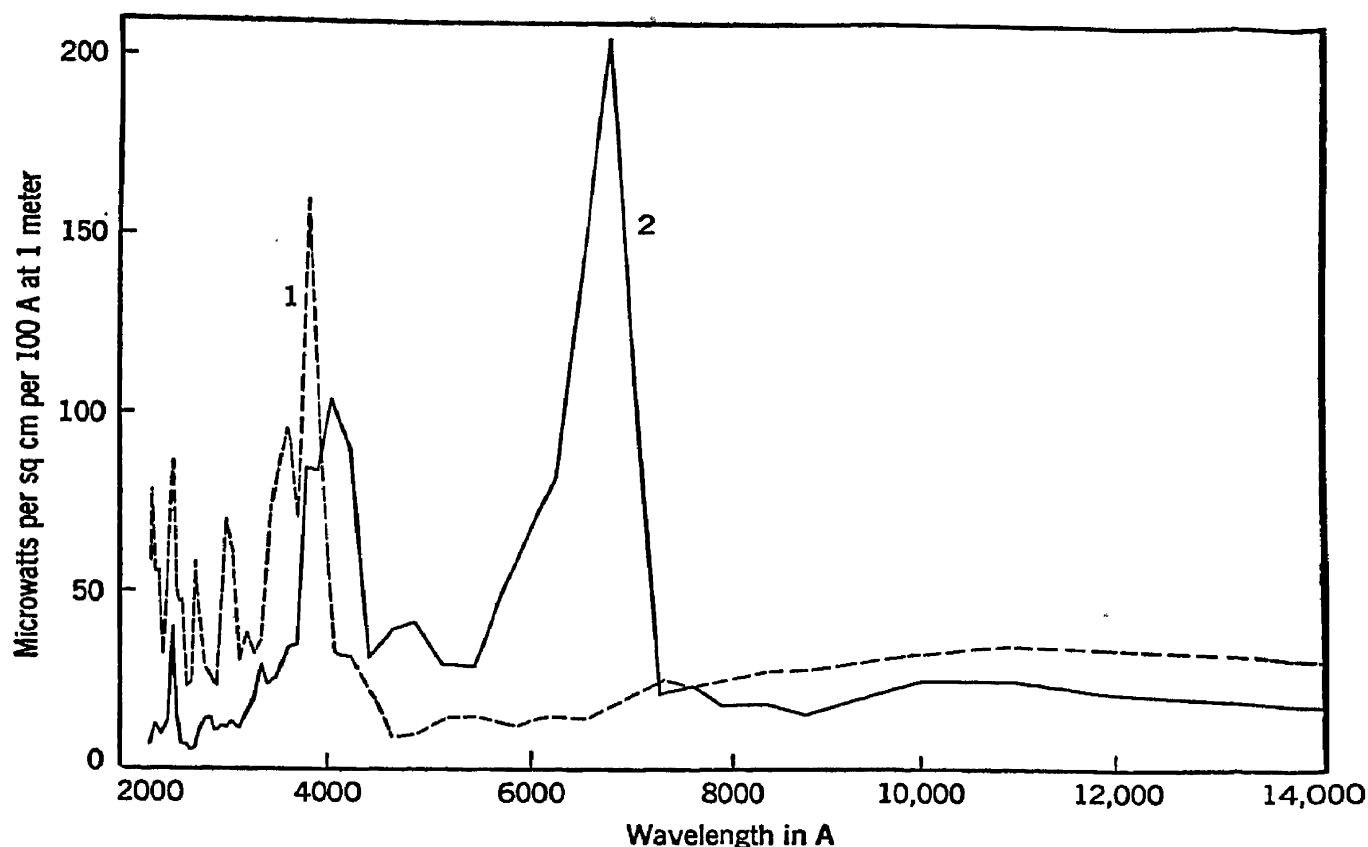
The flame arc employs electrodes consisting of a hard carbon shell containing a core of specially selected metallic salts. In operation, these salts vaporize in the arc and form a luminous flame, the color of which depends on the nature of the salts. The so-called "white-flame" carbons, used for photographic purposes to simulate sunlight, have cores containing the fluorides of the rare earths. Red-flame carbons contain strontium, blue-flame carbons iron, yellow-flame carbons calcium, and so on. Sometimes the metals are incorporated, not in the form of their salts, but as the metals themselves, powdered and mixed with carbon flour, or as rods. The spectra of the flame arcs consist of the continuous spectra due to the hot positive electrodes, and intense line spectra resulting from and characteristic of the metals in the cores. The visual radiation is due primarily to the luminescence of the vapors. In addition to producing intense emission in the spectral regions characteristic of the metals, the addition of metals to the cores often reduces the intensity of the cyanogen band.¹⁵ The intensity of the radiation emitted by an arc increases as the current increases, but is independent of the size of the carbon. Arcs are usually operated on direct current, but some of them can be run on alternating current without much loss in the output of radiant energy.

There are many varieties of arc available commercially, and reference should be made to the extensive literature for information about their characteristics. By way of example, however, data are presented in the form of curves and tables to show the spectral-energy distribution of the radiation from a number of arcs manufactured by the National Carbon Company. All carbon arcs emit the greater part of their energy in the infrared, and much of it is in the long-wavelength region and can be classified as heat. They are all very suitable sources of infrared in the region which can be photographed.^{7, 8, 35, 36, 50}

Table XVI shows the amounts of energy of ten kinds of carbon arc in bands through the spectrum divided approximately as follows: 3,400–7,000 Å, 7,000–14,000 Å, wavelengths above 14,000 Å.

In addition, a number of curves are presented (Figure 35, A and B) which show the spectral-energy distribution of some of the arcs in the ultraviolet, visible, and infrared to 14,000 Å.

In the mirror arc and the high-intensity carbons, the spectra are continuous in the true sense of the word. The spectra of the Eveready Sunshine carbons and the National Motion Picture



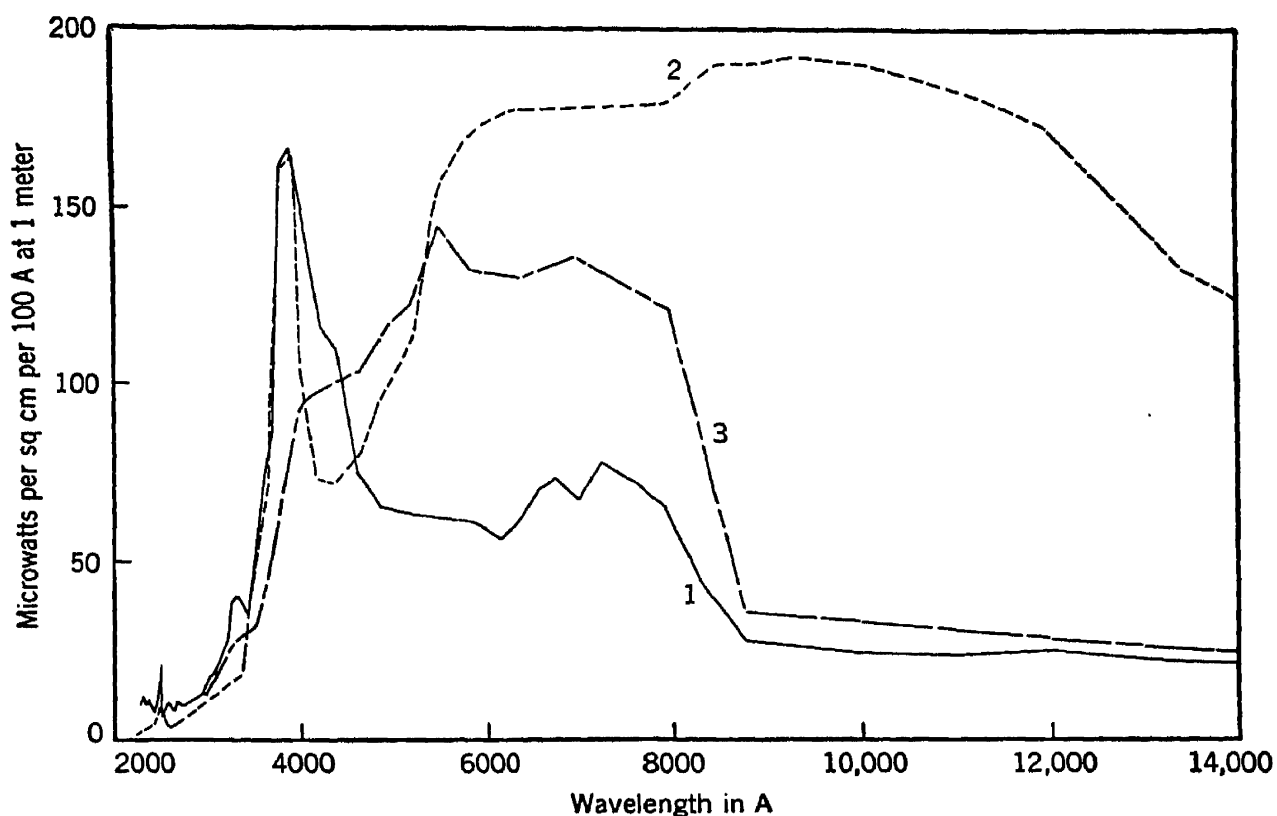
- A. 1. National Therapeutic C carbons, 30 amperes, 50 volts, alternating current.
2. National Therapeutic E carbons, 30 amperes, 50 volts, alternating current.

FIG. 35. Spectral-energy-distribution curves for five types of carbon arc.
(Courtesy National Carbon Company)

Studio carbons consist of the normal continuous background together with an enormous number of lines throughout the spectrum. These lines are so close together that to all intents and purposes they give a continuous spectrum. They can be resolved individually only in a spectrograph of high dispersion. There are also continuous and line spectra associated with the Therapeutic C and Therapeutic E carbons. In the Therapeutic C carbons the metals in the core are iron, aluminium, and nickel, and the majority of the lines are in the ultraviolet. The Therapeutic E carbons are cored with strontium, and the continuous spectrum

has superimposed upon it the characteristic lines of the spectrum of strontium, which are most strongly evident in the red.

It will be clear from a study of Table XVI and the curves, that all the carbon arcs radiate much energy in the near infrared which can be recorded photographically. Certain of them are particularly rich in the rays in this region. Any studio which



- B. 1. National Sunshine carbons, 30 amperes, 50 volts, alternating current.
2. National 12-mm right-angle mirror arc, 30 amperes, 55 volts, alternating current.
3. National White Flame carbons, 8-mm copper-coated, M. P. studio carbons, 40 amperes, 375 volts, direct current.

FIG. 35 (continued).

is equipped with arcs is thus able to make satisfactory infrared photographs. It is simply necessary to select the kinds of carbon which are efficient in the infrared. These include the mirror-arc carbons, Eveready Sunshine carbons, high-intensity carbons, and motion-picture-studio carbons.

Quantitative data concerning the spectral-radiation characteristics of other makes of arc are usually available from the manufacturers. The data presented here apply specifically to the products of the National Carbon Company. In most cases they

TABLE XVI

Type of Carbons	Current	Type of Arc	Source of Light	Current Am-peres	Voltage	Radiant Energy, Microwatts per Sq Cm at 10 Ft from Arc			
						3,400-7,000 A	7,000-14,000 A	14,000-50,000 A	Total
						Per cent	Per cent	Per cent	
"Sunshine" ½ in. uncoated carbons	Alternating	Flame	Flame	30	50	322 43.2	151 20.3	271 36.5	744
National MP studio carbons	Direct	Flame	Flame	40	37.5	862 36.4	590 24.9	916 38.7	2,368*
12-mm low-intensity projectors	Direct	Low-intensity	Positive crater	30	55	502 17.6	892 31.7	1,447 50.7	2,841
"Suprex" 6-mm positive	Direct	High-intensity	Positive crater	30	28	261 30.9	238 28.2	346 40.9	845
"Suprex" 6-mm positive	Direct	High-intensity	Positive crater	40	32	430 35.6	327 27.0	454 37.4	1,211
"Suprex" 8-mm positive	Direct	High-intensity	Positive crater	65	38	877 41.0	553 25.8	710 33.2	2,140
9-mm H.I. projectors	Direct	High-intensity	Positive crater	70	49	1,098 37.0	792 26.7	1,074 36.3	2,964
11-mm H.I. projectors	Direct	High-intensity	Positive crater	90	56.5	1,249 35.3	1,021 28.8	1,270 35.9	3,540
13.6-mm H.I. projectors	Direct	High-intensity	Positive crater	125	63	2,133 33.5	2,027 31.8	2,200 34.6	6,360
16-mm H.I. sun arc	Direct	High-intensity	Positive crater	150	82	3,900 36.8	3,080 29.1	3,620 34.1	10,600

* Energy values for two arcs in series, as this type of arc is always used in twin-arc lamps with two pairs of carbons on 110-120 volts direct current. These various carbons are used in the following branches of the motion picture industry:

Photography

Sunshine carbons, uncoated, ½ × 12 in.
 National MP studio carbons.
 9-mm high-intensity carbons.
 13.6-mm high-intensity carbons.
 16-mm high-intensity carbons.

Projection

12-mm low-intensity projector carbons.
 6-mm Suprex high-intensity carbons.
 8-mm Suprex high-intensity carbons.
 9-mm high-intensity projector carbons.
 11-mm high-intensity projector carbons.
 13.6-mm high-intensity projector carbons.
 16-mm high-intensity carbons.

may be taken as typical. Although methods of preparation naturally differ somewhat, the arcs themselves usually will betray their composition to investigators provided with spectroscopes. For a note on arcs of English manufacture, see page 174.

OTHER ARCS

A well-known arc lamp called the "Pointolite" or "Tungs-arc" consists of a glass bulb containing an inert gas, a tungsten ball as the positive electrode, and a tungsten coiled filament as the cathode. In starting, the current is first passed through the coil which is heated to incandescence, and an arc is formed between the ball and the coil, one side of which is disconnected after the arc is struck. The ball serves as a steady concentrated source of light of high brightness. In the case of the 100-candle-power lamp the temperature of the ball is about $2,920^{\circ}$ K. It is thus a good source of infrared radiation and should be specially suited for infrared photomicrography.

One type of flame arc is known as the magnetite arc and has a negative electrode of copper and a positive electrode consisting mainly of magnetite (iron oxide), titanium, chromium, and alkali salts packed in an iron sleeve.

For spectroscopic purposes, carbon rods are often replaced by metal electrodes, and the spectra are characteristic of the metal. An arc in which the electrodes are of cadmium emits a strong red line which is used as the fundamental standard of wavelength. An iron arc is used as secondary and tertiary standards of wavelength. It is very rich in spectral lines, the wavelengths of some two hundred of which have been determined carefully in terms of the standard cadmium line. Many tables are available which give the wavelengths of the lines in the spectra of these and other elements. Instead of pure metallic electrodes, carbon rods are sometimes employed, salts of metals being placed in the crater to produce the desired lines. This method is used in spectrographic analysis, the unknown material being placed on the positive carbon. The spectrum permits identification of the elements present.

OTHER SOURCES

There are many other sources of continuous radiation which have been used for a variety of purposes and which have the

major part of their radiation in the infrared. None of them is so efficient as those already mentioned, since they operate at relatively low temperatures. They include candles and oil lamps, the acetylene flame, the Bunsen burner and other gas burners, the kerosene lamp, the pentane lamp, the Hefner amyl acetate lamp, the Carcel colza oil lamp, and other lamps burning other hydrocarbons. Although none of these can compare with the incandescent tungsten filament, arc, and Photoflash types of lamp for the purposes of practical infrared photography, certain of them are of great importance in that they form standard sources for photometric measurement of radiation.

In the thorium lamp, a stream of electrons is made to impinge on a block of thorium in an evacuated bulb. The spectrum is effectively continuous and is particularly strong in the ultraviolet. It extends to about 6,000 Å, but is nearly free from infrared radiation. The underwater spark gives spectra which are essentially continuous, and of equivalent color temperature which may be as high as 10,000° K in the case of a strong spark. These sources are strong in the visible and ultraviolet, but are not of importance for infrared work.

SOURCES WITH DISCONTINUOUS SPECTRA

The incandescent light sources emit light and infrared solely because of their high temperature, and they always produce a continuous spectrum. There is another great class of sources which comprises those that may be called luminescent radiators, in which the radiation is produced by the passage of electricity through gases. Their spectra are not continuous, but consist primarily of lines or bands which are characteristic of the nature of the gas through which the electric discharge occurs. At times there may be more or less continuous spectra associated with the lines, but the main feature consists of selective emission at certain definite wavelengths. Unlike the incandescent sources, the luminescent sources are not primarily dependent on their operating temperature for the determination of their spectral quality.^{4, 16, 28, 31, 52, 57, 61, 63}

The flame carbon arcs might reasonably be classed as sources of selective emission. It is considered desirable, however, to treat all the carbon arcs in one group, and the flame arcs, there-

fore, are discussed in the section on sources of continuous radiation, with the plain arcs which emit essentially continuous spectra.

In recent years, great advances have been made in the development of lamps giving discontinuous spectra, but commercial lamps are confined mainly to the use of mercury, neon and other rare gases, and sodium as the gaseous conducting material. In the following sections brief surveys are made of the main characteristics of these and some other lamps. It should be mentioned at the outset that most of them do not provide very suitable sources for general infrared photography, although their infrared spectra are of considerable interest for a number of special purposes, particularly in the field of spectrography.

MERCURY ARCS

The mercury arc in the form of the Cooper-Hewitt mercury-vapor lamp was developed in 1901 and placed on the market shortly afterwards. It consisted of a glass tube containing two metal terminals which were connected to a source of electric current. The lamp was evacuated as much as possible and contained a pool of mercury. To start such a lamp, the electric current was switched on, and the lamp was tilted, causing the mercury to run through the tube to form a conducting link between the terminals. As soon as this link was broken, an arc discharge occurred, much in the way that a carbon arc is struck by allowing the carbons to touch and then separating them. An alternative method of starting the arc consisted in applying a high potential across the electrodes so as to ionize the mercury vapor that was present even when the tube was cold.

Soon after the introduction of this lamp, many attempts at improvement were made, particularly with the object of making up for the deficiency of red in the light from it. To effect this, other metals were added to the mercury, special fluorescent reflectors were employed, and so on. For medical and scientific purposes, quartz was used to replace the glass of the tube so as to allow much of the ultraviolet to pass. Other lamps were devised in which there was a considerable pressure of mercury vapor, and in another form, the so-called "sunlight lamp," a mercury discharge passed between two hot tungsten cylinders in a bulb

similar in shape to that of a normal electric lamp. Later lamps were devised in which rare gases were introduced into low-pressure mercury tubes, and the electrodes consisted of oxides of the alkaline earths, heated by a tungsten filament. To provide a continuous spectral background fluorescent lamps now are made with a coating of fluorescent materials inside the tubes.

In a very efficient type of mercury arc, known as the high-pressure mercury lamp, oxide-coated electrodes are used, and the mercury is at a relatively high pressure. The tube contains a low pressure of the rare gases, and metals other than mercury are added to increase the output of red light. A limited quantity of mercury is used, and this is all vaporized before the normal operating temperature is reached. The lamps, therefore, are little affected by heating and cooling due to changes in ventilation, and in this respect they show superiority over the earlier lamps. A more recent form of mercury lamp consists of a quartz capillary tube only a few centimeters in length and a few millimeters in diameter. It operates at mercury-vapor pressures up to 40 atmospheres in the open air and several hundred atmospheres when water-cooled.^{4, 16, 41, 61}

The radiation from the low-pressure lamps of the Cooper-Hewitt variety consists almost entirely of the lines of the mercury spectrum. The lamps which contain a higher pressure of mercury also show a continuous spectrum of moderate intensity spread more or less uniformly through the visible and near-infrared spectrum. As the mercury pressure in the lamps increases, the continuous radiation becomes more and more important, so that, in the case of certain of the capillary lamps, about 25 per cent of the light may be in the continuous spectrum. This background becomes particularly strong in the red and near infrared.

The main lines in the spectra of the higher pressure lamps lie in the same position through the spectrum as those of the low-pressure lamps, although their relative intensities are different and they are broader. Moreover, the presence of metals other than mercury and of the rare gases adds lines other than those of the mercury spectrum.

Table XVII, kindly provided by Dr. W. E. Forsythe, shows the radiation characteristics of a number of different types of mercury arc.⁴ The lamps cover the range of mercury arcs generally

TABLE XVII
RADIATION OUTPUT OF A NUMBER OF MERCURY LAMPS

<i>Lamp</i>	<i>Quartz Uniarc for 110-Volt Line</i>	<i>Cooper-Hewitt Low-Pressure Mercury Arc</i>	<i>250-Watt Type-H Mercury Arc</i>	<i>400-Watt Type-H Mercury Arc</i>	<i>Mercury Capillary Lamp (Enclosed)</i>	<i>Mercury Capillary Lamp (Unen- closed)</i>
<i>Operating Characteristics</i>						
Volts	75.0	71.9	67.5	150.0	251.0	250.0
Amperes	3.75	3.70	4.06	2.77	0.401	0.403
Watts *	281.0	266.0	250.0	400.0	85.6	85.6
Inside tube diameter	1.5 cm	2.4 cm	2.5 cm	3.5 cm	0.4 cm	0.4 cm
Arc length	8.5 cm	128.0 cm	10.5 cm	16.0 cm	1.7 cm	1.7 cm
Lumens	8,500.0	6,500.0	7,000.0	16,000.0	3,380.0	3,139.0
Lumens per watt	30.0	24.5	28.0	40.0	39.5	36.5
<i>Wavelength</i>	<i>Spectral Intensities † for Different Wavelength Bands</i>					
17,100-16,900 Å	11.6	...	11.9	34.4	6.9	7.8
15,300 Å	3.6	...	7.9	27.1	6.1	6.7
13,955-13,570 Å	12.8	...	14.8	44.0	8.5	8.9
12,100-11,900 Å	3.6	...	8.2	27.4	6.3	6.4
11,289 Å	9.2	...	12.5	35.7	7.8	7.6
10,140 Å	21.6	35.8	22.7	69.0	10.8	10.5
7,420-6,835 Å	...	...	3.3	...	3.75	3.8
7,087 Å	0.8	...	...	...	...	...
6,835-6,350 Å	...	...	2.3	5.7	3.0	3.05
6,350-5,945 Å	...	...	1.9	5.6	3.1	2.93
6,234 Å	0.6	...	...	...	...	...
5,780 Å	73.0	26.6	55.0	127.0	19.2	17.0
5,461 Å	66.0	81.4	57.5	131.0	33.5	31.5
5,315-5,065 Å	...	...	1.24	4.5	2.2	2.11
5,065-4,840 Å	...	...	1.47	3.02	2.05	2.03
4,916 Å	1.9	...	...	...	...	...
4,840-4,645 Å	...	...	0.63	...	2.2	2.3
4,645-4,475 Å	...	...	0.62	...	2.6	2.6
4,358 Å	58.0	83.0	44.5	92.0	27.1	25.8
4,047 Å	34.1	59.0	23.6	44.5	14.5	14.0
3,904 Å	1.53	...	...	...	...	...
3,654 Å	103.0	29.2	22.5	41.0	25.7	24.4
3,341 Å	7.7	2.6	...	...	3.2	3.44
3,129 Å	71.0	13.3	...	...	6.9	14.8
3,022 Å	31.4	0.28	...	...	1.21	6.5
2,967 Å	15.6	0.097	...	...	0.73	5.8
2,925 Å	1.9	...	...	...	...	1.64
2,894 Å	5.7	...	...	...	...	2.6
2,804 Å	10.9	...	...	...	...	2.66
2,753 Å	3.46	...	...	...	...	2.05
2,700 Å	4.6	...	...	...	...	2.01
2,652 Å	23.4	...	...	...	...	3.16
2,576 Å	4.1	...	...	...	...	...
2,536 Å	32.0	...	...	...	...	0.55
2,483 Å	9.4	...	...	...	...	1.2
2,464 Å	1.47	...	...	...	...	0.56
2,447 Å	1.2	...	...	...	...	0.27
2,399 Å	4.0	...	...	...	...	0.54
2,378 Å	3.6	...	...	...	...	0.68
2,353 Å	2.14	...	...	...	...	0.76
2,323 Å	1.33	...	...	...	...	0.73
2,302 Å	2.13	...	...	...	...	0.72
2,259 Å	1.36	...	...	...	...	0.33

* For the lamp alone.

† Microwatts per square centimeter at 1 m from lamp.

available commercially. Although they are the products of one manufacturer only, they may be regarded as typical. Specific data on other lamps can be obtained usually by writing to the manufacturers concerned (see the note on p. 174). The typical line spectrum shown in Figure 26 is of a low-pressure mercury arc.

It may be observed that the only important lines in the infrared spectra of the radiation from these lamps, in the photographic region, are at 10,140 and 11,289 Å. For general purposes of infrared photography, the mercury arc is not nearly so convenient or suitable as the high-efficiency tungsten-filament lamps. It is, however, a most satisfactory source of relatively monochromatic radiation and on this account is of considerable importance for a variety of special purposes.

The fluorescent lamp, which is very popular as a source of general lighting and for certain photographic purposes, is a low-pressure mercury-vapor-discharge lamp, the inside of the tube of which is coated with a mixture of materials which fluoresce in the short-wavelength ultraviolet produced in the tube. The mixture is selected to give a desired spectral quality of light.^{33, 47} The fluorescent lamps are not suited for infrared photography.

SODIUM-VAPOR LAMPS

The sodium-vapor lamp has been introduced commercially, and has even found application for street-lighting purposes.^{16, 57} Its success depends on the use of hot oxide electrodes and a special glass which will withstand the action of hot sodium vapor. The discharge occurs in sodium vapor in a tube surrounded by a jacket evacuated to reduce heat developed by the discharge and to keep up the temperature of the sodium as much as possible. The tube contains a few millimeters' pressure of rare gas in order to start the discharge, since at ordinary temperatures only a negligible amount of sodium exists as vapor. A mixture of neon with a trace of argon usually is employed.

The radiation from this kind of lamp consists of the line spectrum of sodium modified by that of the neon. The bulk of the energy is in the sodium D lines in the yellow at 5,896/90 Å. In the infrared, the chief lines are in pairs at 8,195/83 and

11,404/382 Å. As in the case of the mercury-arc lamps, the sodium-vapor lamps are of little value for general infrared photography.

NEON LAMPS

The neon lamp has been much used commercially, particularly for advertising signs. Like the low-pressure mercury tube, it has been used for many years in the form of the cold-cathode neon tube. It also has been made available in the much more efficient form of the hot-cathode neon-discharge lamp.¹⁶ The neon spectrum is characterized particularly by a large number of bright lines in the visible red and in the near infrared between 7,000 and 9,000 Å.

OTHER GASEOUS-CONDUCTION LAMPS

The three lamps previously described are the most important commercially, but much study has been devoted to discharges in other gases and metallic vapors.^{16, 31, 41, 48, 52, 57, 61} These include nitrogen, helium, argon, carbon dioxide, hydrogen, lithium, potassium, cadmium, zinc, and thallium. The familiar glow-discharge lamps, such as the Geissler tube, are available filled with a large variety of gases and vapors and have been much used as sources for spectrographic work and for display purposes. None of them is of value for general infrared photography.

An important photographic light source is the gaseous condenser-discharge lamp evolved by H. E. Edgerton and made available in a variety of forms, notably the Kodatron Speed-lamp.^{18, 59, 60} It consists essentially of a glass tube containing a mixture of rare gases and two electrodes connected across a condenser which can be charged to a high voltage. The pressure of the gases is too high for spontaneous discharge of the condenser, but it can be made conducting by a third high-potential electrode external to the lamp, and, when this is done, the condenser discharges all its stored energy through the lamp in a single surge. The result is a very bright flash of extremely short duration—in the case of the Kodatron lamp about 1/10,000 second. The light from such a lamp has a continuous background of spectrum, on which are superimposed strong lines characteristic of the gases

in the tube. The spectrum shows a slight excess of blue light, and there is adequate emission in the near infrared to permit short-exposure infrared photographs to be made (see Figure 36).

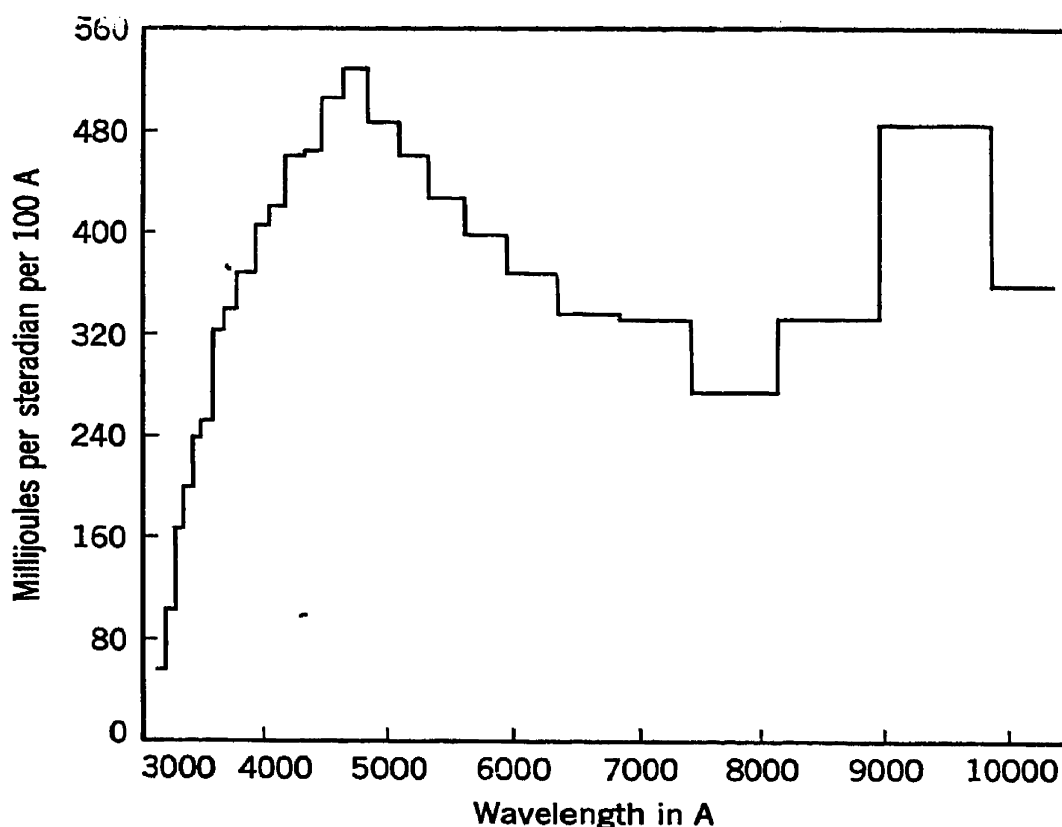


FIG. 36. Typical spectrum of Edgerton gaseous condenser-discharge lamp. The curve shows the spectral energy radiated along the axis of a Type FT-15 flash tube with 56- μ f supply at 2,000 volts.

(From Lamp Development Laboratory, General Electric Company)

THE SPARK

A source much used in spectrographic work is the electric spark formed between suitable metal electrodes. The line spectrum of the spark is that of the metal of the electrodes, but gases and liquids may also be introduced. Sources of this kind are of no value for general infrared photography, although they are used in conjunction with the spectroscope.

PRACTICAL SELECTION OF SOURCES FOR INFRARED PHOTOGRAPHY

As a convenience for the practical photographer, the types of infrared source most suited to the various applications of infrared

photography are summarized in the following. The selection of filters for use in conjunction with the sources has been discussed in various chapters of this book.

GENERAL PHOTOGRAPHY

Sunlight.

Tungsten-filament lamps of high efficiency: lamps of 500 watts and higher; Photoflood and Movieflood lamps; projector type lamps; all types of tungsten-filament studio lamps.

Carbon arcs: flame, neutral-cored, and plain arcs, all types of studio and projection arc.

Photoflash and Superflash types of lamps.

Kodatron Speedlamp.

CINEMATOGRAPHY

Sunlight.

All types of tungsten-filament and arc lamps normally used for studio work.

MEDICAL PHOTOGRAPHY

All the sources grouped under "General Photography."

PHOTOMICROGRAPHY

Tungsten-filament lamps as used in normal photomicrography, especially the ribbon-filament lamps.

Carbon-arc lamps.

Enclosed metallic arcs, especially the Fointolite and Tungs-arc type of tungsten arc.

Mercury capillary lamps.

DOCUMENTARY, GRAPHIC ARTS, CRIMINOLOGY, SCIENTIFIC-RECORD PHOTOGRAPHY

All the sources grouped under "General Photography."

PHOTOGRAPHY IN THE DARK

The artificial sources given under "General Photography."

SPECTROGRAPHY, RADIATION MEASUREMENT

Any source of continuous or discontinuous radiation mentioned in this chapter, selected according to the purpose.

NOTE ON CHARACTERISTICS OF LAMPS OF ENGLISH MANUFACTURE

The data in this chapter relating to the energy characteristics of incandescent tungsten-filament electric lamps, carbon arcs, and mercury-discharge lamps apply specifically to products of American manufacture. In the United States general lighting service lamps are usually operated at 115 volts. In England the lamps are mostly designed for 200–260-volt supplies. For tungsten-filament lamps of English manufacture, the relative spectral distribution can be taken, according to the value of the luminous efficiency of the lamp, from the data given in this chapter; the actual magnitude of the energy values will depend on the wattage of the lamp.

For carbon arcs and mercury-discharge lamps the data given in respect of the infrared radiation will apply generally in the case of sources of similar type and dimensions, provided the electrical running conditions are the same.*

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* The author is indebted to C. C. Paterson, director of the research laboratories of the General Electric Co., Ltd., for this statement.

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Chapter VIII

EXAMINATION AND DIFFERENTIATION OF MATERIALS BY INFRARED

Infrared photography owes most of its value to the fact that many materials reflect and transmit infrared and visible radiations to different extents. It is thus possible by its means to see through some materials which are visually opaque, and to show contrast between things which appear equal both to the eye and in an ordinary photograph. This has made it a very helpful implement in many fields of special investigation. In this chapter we shall deal with its application in the textile and graphic arts industries, in the examination of paintings and documents, and in criminology. Much relevant material also may be found in Chapter XII, and particularly in Chapter XIII dealing with camouflage detection and in Chapter XVI which treats of the optical characteristics of a number of materials in the infrared.

TEXTILE INDUSTRY

In the textile industry, irregularities in the dyeing or weaving of cloth and damage to fibers as the result of excessive action of finishing solutions are difficult to study visually when the cloth or yarn is dyed in dark colors. Photography by means of panchromatic materials and filters usually does not help very much. Most dyes, however, exhibit characteristics of reflection and transmission in the infrared which are different from those in visible light. Infrared photography, therefore, should be of assistance in the examination of them, and it has been much studied in England and Germany in connection with textile problems.

In general, it may be stated that there are no dyes so far reported which appear light to the eye and dark in the near infrared, whereas there are many cases of dyes which are dark to the eye and which reproduce as light in an infrared photograph.

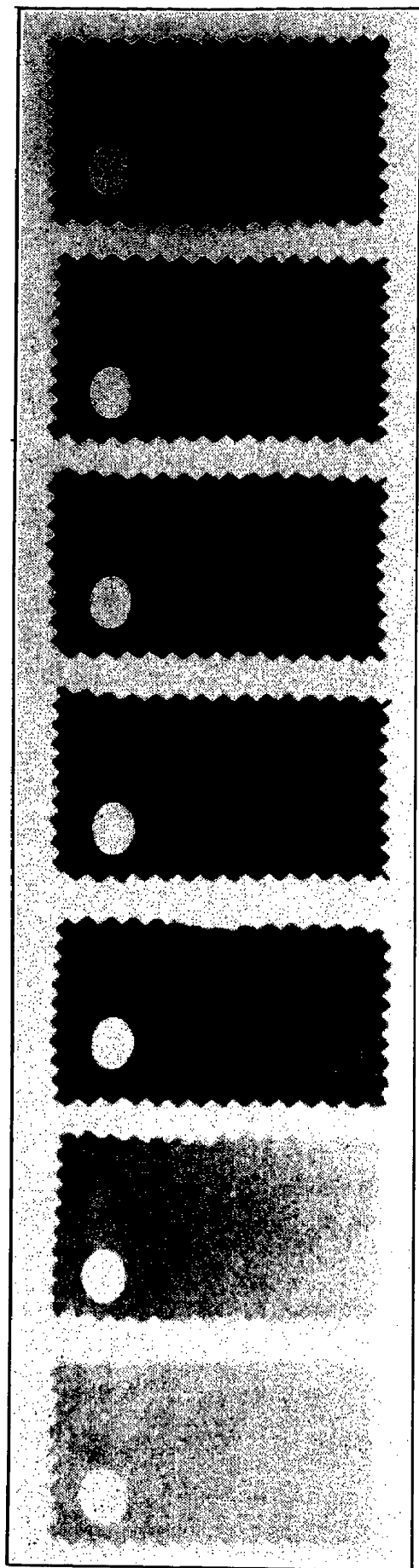
Systematic series of photographs of dyed swatches which illustrate this have been published by various workers, particularly Cunliffe,¹³ Bloch,^{8, 9} Fröhlich²¹⁻²³ and Danckwortt.¹⁵

It is usually found that, if comparison photographs are made by visible and infrared radiations, cloth which is dyed in light colors, particularly yellows and reds, reproduces by infrared in more or less the same manner as it does by visible light. On the other hand, differences may appear in infrared photographs of dark colors which are difficult to distinguish by eye and which appear as more or less equally dark in normal photographs. The behavior varies according to the region of the infrared used, and, in general, the reflection increases with the wavelength. Fröhlich recommends the region 8,400–9,000 Å as the most useful. Some idea of the manner in which the reflection of differently dyed dark cloths varies in the infrared may be obtained from Table XVIII, which is due to this investigator²¹

TABLE XVIII
INFRARED REFLECTIVITY OF DARK CLOTHS

	<i>Dye</i>	7,300 Å	8,550 Å	10,600 Å
Green	Fast Green CR	Grey	White	White
	Algol Brilliant Green 3K Tg	Black	White	White
	Anthraquinone Green GXNO	Black	White	White
	Alizarine Brilliant Green SE	Black	White	White
Blue	Algol Blue 5R	Grey	White	White
	Indanthrene Blue BCS Plo	Black	Grey	White
	Hydron Blue R	Black	Grey	White
	Immedial Indone BBF	Black	Black	Grey
Brown	Indanthrene Brown BR	White	White	White
	Eriochrome Brown Chr	Grey	White	White
	Diachrome Brown TV	Grey	Grey	White
	Immedial Brown BR	Black	Black	Grey
Black	Naphthol AS-SW Fast Black Salt K	Black	Black	Grey
	Naphthol AS-SW	Black	Grey	White
	Diamond Black F	Black	Grey	White
	Chrome Black M Melequano	Black	Black	Black

The figures at the heads of the last three columns refer to the position in angstroms of the maxima of sensitivity of the photographic plates used. The terms white, grey, and black refer



qualitatively to the density of the positives. In each group the colors appeared identical to the eye.

Cunliffe¹³ published the results of observations on the rendering of a very large number of wool and cotton dyeings in the near infrared about 8,000 Å. His results agree with those of Fröhlich in showing that all the visually light shades photograph as light, while the dark shades may appear as anything from black to very light. For instance, 8 per cent Acid Black ZH reproduces as white, whereas Acid Black G appears grey, and most chrome blacks are rendered as black.

Figure 37 shows an infrared photograph of a series of swatches of black dyed cloth which could not be distinguished one from the other by visual examination. By infrared they range from light grey to black. In Figure 38 are shown photographs of a doll made on a panchromatic plate and on an infrared plate. The doll was dressed in clothes made from two pieces of black cloth which were visually identical. The difference in the infrared reflecting powers of the two kinds of material is clearly evident. The result of a very extensive study of the photographic reflectivity of black dyes in the infrared was published by Danck-

FIG. 37. Infrared photograph of seven swatches of black cloth.

The pieces of cloth all were equally black to the eye. The illustration shows how the reflectivity of black dyed materials may vary in the infrared.

wortt¹⁵ in 1939. Over 200 dyes were investigated from among the I. G. Farbenindustrie acid and chrome dyes, and the results are tabulated in the article.

The infrared reflectivity of different dyes is determined by their constitution and by the nature of the dyeing. Fröhlich



FIG. 38. Photographs by A, visible light, and B, infrared, of a doll dressed in black cloth.

The clothes were made of two pieces of black cloth which appeared identical to the eye. B shows the difference in their reflectivities in the infrared.

points out that, as a result of treatment with chrome salts, for instance, the behavior of a dye towards the infrared may be much changed, whereas its visual color is unaffected.

In the handling of materials of black or other dark shades, there is difficulty in distinguishing faults by daylight or artificial light. Infrared photography helps in such cases. Cunliffe¹³ quotes an instance of a dark-blue bathing suit which was found to bleed in an unusual manner, but which appeared as quite even to the eye. An infrared photograph showed a regular series of

bars which indicated a possible cause of the trouble, and it was actually found that the portion giving the streaks was dyed with a different dye from the remainder. Similar results are mentioned by Fröhlich.²¹ Black, brown, or blue fabrics which appeared uniform in color sometimes showed unexpectedly poor fastness, and infrared photographs revealed that the yarn had been dyed with dyes which appeared the same to the eye but which were actually different. For instance, in one case some of the yarn was dyed with Acid Alizarine Black 3B Extra, and the rest with Naphthol AS-SW and Fast Black Salt K. Results similar to those of the investigators previously mentioned have also been reported by Reumuth and Köhler.⁵⁹ If it is suspected that the yarn itself is spun from a mixture of differently dyed fibers, it is merely necessary to tease it out somewhat and to photograph it by infrared at a low magnification. The structure of the weave often appears more clearly in infrared photographs of dyed cloth.⁵¹

The use of infrared photography in the selection of dark clothes for wear in summer and winter has been proposed a number of times (Bloch,⁸ Cunliffe,¹³ Fröhlich²¹). It would be expected that dyes which transmit infrared rays and, therefore, photograph as light when applied to cloth would be cooler than those which absorb the infrared and so photograph as dark. Although this is true to some extent, it should be realized that the infrared which can be photographed is only a part of the heat spectrum emitted by the sun and artificial heating appliances, and radiated from the body. Reflection characteristics of a dyed cloth in the wavelength region longer than the photographic infrared must play a big part in determining the warming or cooling effect of clothes. It is known that, as the wavelength increases, the infrared reflection may change considerably. In addition, the structure of the cloth itself plays a very important part.

Use can be made in photomicrography of the change in reflecting power and transparency of dyed fibers in the infrared.³¹ Clearly, it is practically impossible to make useful photomicrographs of black and brown fibers by the normal photographic method. Many of the dark pigments are transparent to infrared, so that photomicrographs by infrared radiation are sometimes able to reproduce the detail in the fibers as if they were undyed.

Reumuth and Köhler⁵⁹ quote an example of the use of infrared photomicrography in the study of dyed fibers which had undergone excessive degreasing in washing. Another example is given of a cloth which was found to consist of a mixture of cotton, wool, and artificial silk, but which was dyed black so that the content of artificial fibers could not be detected without the aid of infrared photography. Further, in the examination of black dyed cotton, when Fehling's reaction is used, infrared photography shows up crystals of copper oxide which may be precipitated on the fibers, whereas they are not distinguishable visually. Examples of infrared photomicrographs of cloths are given in Chapter XI (pp. 290-3).

Other applications of infrared photography in the textile field have been investigated, and doubtless further uses have been found than those already mentioned. Cunliffe states that the method has not proved of value in the investigation of mildew and bacterial stained wool. Reumuth and Köhler suggested that the infrared procedure might be of value in the detection of metallic foreign bodies in fabrics.

The infrared photography of dyed textiles is of great importance for camouflage, and the interested reader should refer to Chapter XIII for a full consideration of this subject.

GRAPHIC ARTS INDUSTRY

In the reproduction of colored originals by the methods of photomechanical reproduction, difficulty has been encountered in the direct reproduction of all colors by photography alone. Much handwork is usually necessary on the plates before they are suitable for printing. Infrared photography has proved of assistance in eliminating the need for much of this. As in so many other applications, advantage is taken of the fact that many dyes and pigments have reflection and transmission characteristics in the infrared which are quite different from those in the visible part of the spectrum. A study by Murray and Wilhelm⁴⁷ of infrared photographs of common artists' colors showed definite and striking peculiarities. This is significant, because most of the colored originals which the photoengraver has to reproduce are painted by artists using the colors commonly available, either water colors or oils.

With certain notable exceptions, the artist's common colored paints reflect infrared as though they are white, or nearly white. The exceptions include browns, blacks, and the iron double cyanide blues. Using a Winsor and Newton oil-color chart, Murray and Wilhelm found the following characteristics:

Colors which photograph as white or nearly so by infrared:

Purple Lake.	Ultramarine Light.
Permanent Crimson Lake.	New Blue.
Permanent Geranium Lake.	Ultramarine Deep.
Scarlet Lake.	Oxide of Chromium (Green).
Spectrum Red.	Viridian.
Orange Vermilion.	Cerulean Blue.
Cadmium Orange.	Cobalt Blue.
Cadmium Yellow.	Cobalt Violet.
Cadmium Yellow Pale.	Magenta.
Aurora Yellow.	Crimson Lake.
Chrome Yellow.	Rose Madder.
Chrome Lemon.	Rose Madder Alizarine.
Cobalt Green.	Alizarine Crimson.
Vermilion.	Indian Yellow.
Scarlet Vermilion.	Cadmium Yellow Deep.
Light Red.	Aureolin.
Indigo.	Gamboge.
Sky Blue.	Lemon Yellow.
Permanent Blue.	Zinc White.

Colors which photograph as black by infrared:

Prussian Blue.	Milori Blue.
Antwerp Blue.	Chinese Blue.
Cyanine Blue.	Bronze Blue.
Ivory Black.	Lamp Black.

These colors consist of carbon blacks and iron blues only. Greens and other colors in which iron blue is mixed photograph as various densities of grey, depending on the amount of iron blue they contain. Browns photograph as grey also, the density depending on the content of black. Examples of paints on the Winsor and Newton chart which photograph grey are:

Chrome Greens, nos. 1, 2, and 3	Raw Umber.
Emerald Green.	Burnt Umber.
Alizarine Green.	Sepia.
Terre Verte.	Bitumen.

The fact that Alizarine Green falls in this class is probably due to the black component. However, it is not a very important pigment. The light-colored earths, including the siennas, ochres, and iron oxide reds, photograph a light grey in the infrared. The phthalocyanine blues, for example, Monastral Blue, photograph grey in the infrared, and Hansa yellow photographs as white. Reference should be made to Chapters XII and XIII for much further information on the infrared photography of paints and pigments.

A long-standing problem facing the photolithographer is the making of negatives for light blue and dark blue when five or six printing colors are to be used or, as is sometimes done in four-color work, when a dark blue is used but no black. The customary method for differentiating between the printing plates for the two blues comprises hand retouching in one form or another. As a result of the study of the characteristics of paints in the infrared, Murray and Wilhelm⁴⁷ worked out a method for separating the two blues photographically, and so eliminating the need for handwork. It is limited to the reproduction of new designs, specially painted with the process in mind. It will be obvious from the preceding data showing the infrared reflection characteristics of various colors that, if a commercial artist has to create a design to be reproduced in two blues and any other colors, such as red and yellow, he can place his blue pigments selectively so that from his sketch a "light-blue" plate and a "dark-blue" plate can be made by straight photographic methods. To illustrate this, Murray painted a simple sketch in oil colors. A copy of it, made on a panchromatic plate without a filter, is shown in Figure 39A, in which the colors are indicated. The blues used in the sketch were Ultramarine, Cobalt, and Cerulean, which reflect infrared, and Chinese Blue, which absorbs it. The artist must take care in making the sketch that he does not use iron blue where he does not wish the dark blue to print in his reproduction.

Two blue plates are made, one by the normal method of using a panchromatic plate and a red filter, such as the Wratten no. 25, and the other on an infrared-sensitive plate using the Wratten no. 88A filter. The former plate (Figure 39B) is essentially

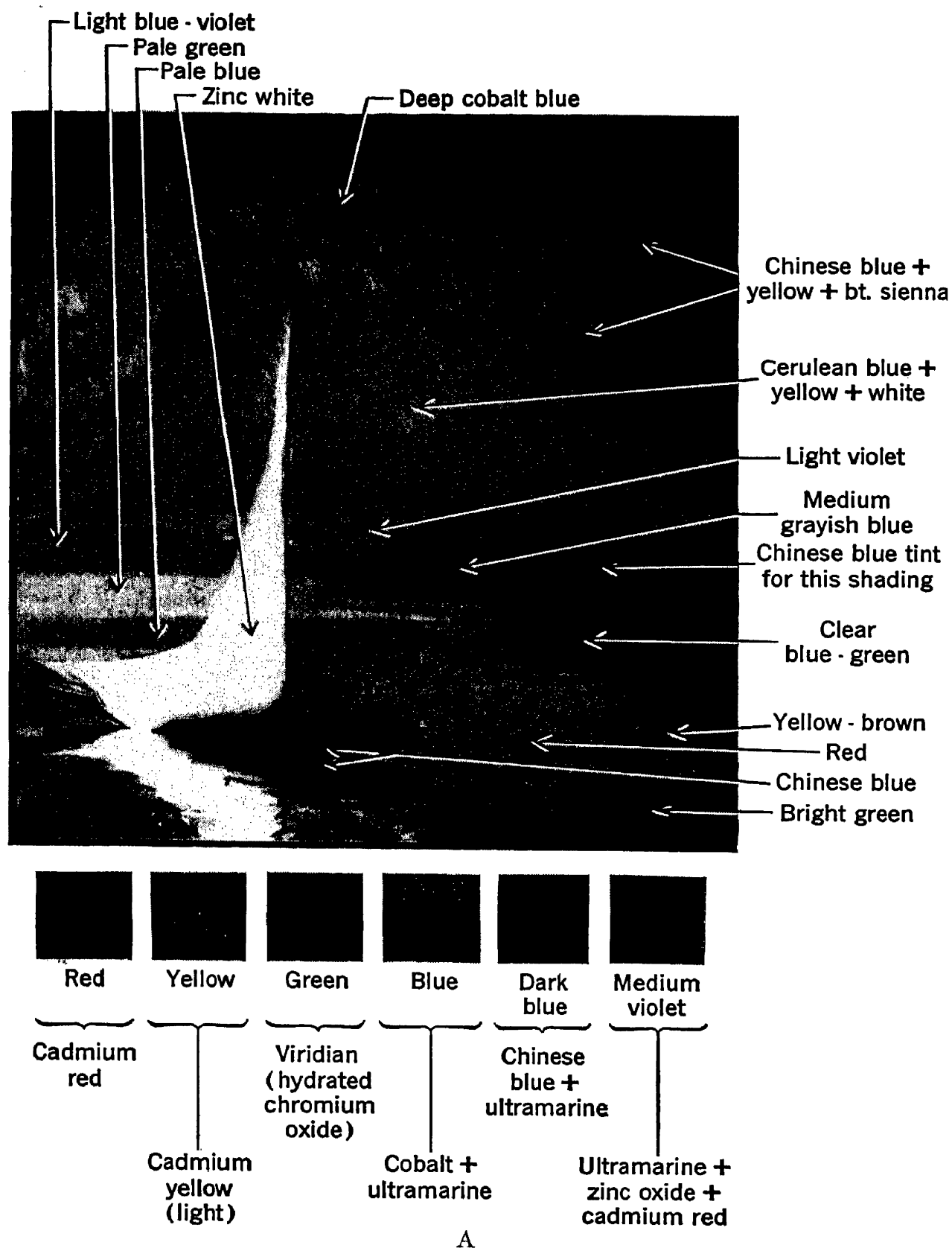
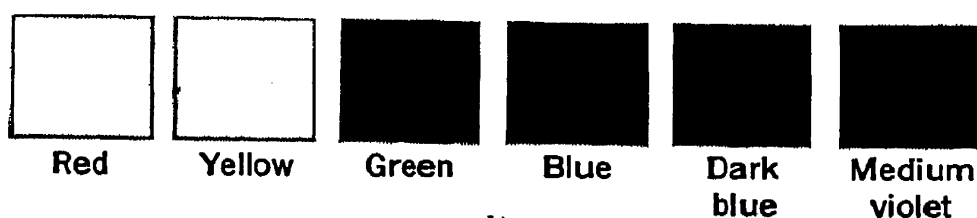


FIG. 39. Photographs of oil painting by A, panchromatic plate with no filter; B, panchromatic plate with red filter; and C, infrared-sensitive plate with the Wratten no. 88A filter.

(A. Murray and G. Wilhelm, Jr.)

correct for a light blue and requires no retouching for color correction. The second (Figure 39C) is an almost fully corrected plate requiring practically no retouching of tones.



B

FIG. 39 (Continued).

In the attempt to find a purely photomechanical method of making color reproductions, in which satisfactory results could be obtained without the need for color correction by handwork, Murray worked out a masking method which was similar in its elements to a method proposed by Albert in 1898, but which had never been adopted in practice to any extent. Murray elaborated the method and introduced careful control measurements. His

procedure is described in detail in a booklet published by the Eastman Kodak Company under the title "The Modern Masking Method of Correct Color Reproduction."¹⁷

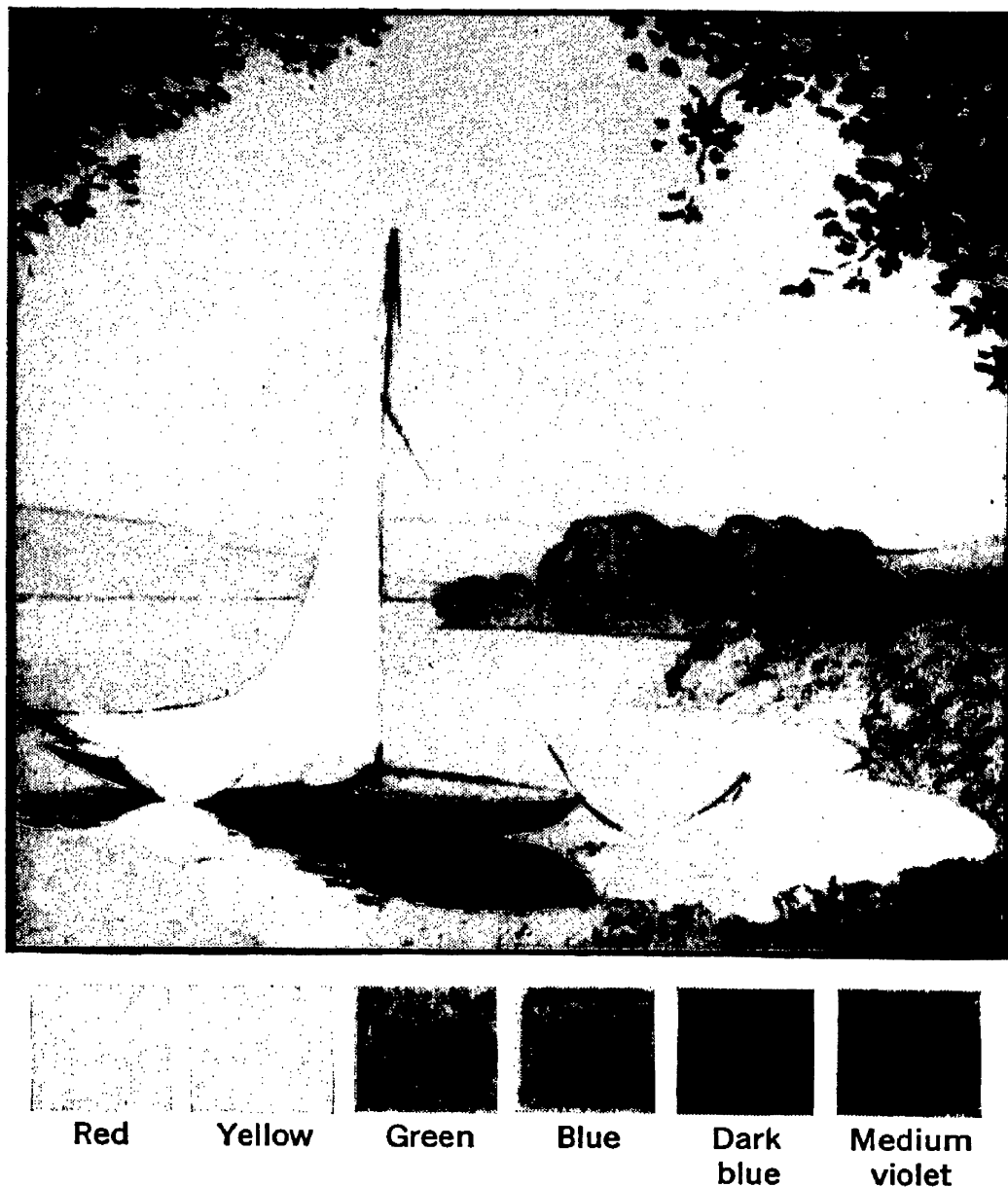


FIG. 39 (Continued).

It is beyond the scope of this work to go into the process at length, and reference will merely be made to the use of infrared photography for preparing the black printing plate. The process is carried out in the usual manner by means of three colors and black. The use of a black plate is desirable because it gives deeper shadows, and the usual way of obtaining the plate is to photograph the subject on a panchromatic plate through a yellow

filter, and to follow this with considerable handwork on the printing plate. Applying the results of his study of the infrared characteristics of artists' colors, Murray prepares his black plate entirely photographically. Most colors, pigments, and dyes reflect a high percentage of infrared and yet absorb enough in the deep shadows to make a black plate by infrared photography which requires no retouching. In preparing the sketch for this, the artist should avoid the use of the few colors which absorb the infrared strongly, and which have been mentioned previously. The elimination of these colors does not by any means paralyze commercial design, although it requires the artist to change his palette and his technique to some extent. Carbon blacks should be used in greys, blacks, and deep shadows. In making the black plate from copy suitably painted, the engraver merely photographs it on an infrared-sensitive plate through a filter, such as the Wratten no. 88A, to confine the exposure to the infrared. From the negative, a black printing plate can be made without the need for hand retouching. Tritton^{69, 70} has described the method and recommended it to printers who control their artists' work, and von Kujawa³² also has dealt with the infrared reflectivity of paints from the point of view of the preparation of the black printer. Some caution should be exercised in reading his paper, for there is confusion between dyes and pigments which may be misleading.

There are a number of other specific applications. Some techniques can now be used by commercial artists which hitherto were barred by inconvenience of reproduction. There are, for instance, several variants of pen-and-wash. An intricate pen drawing can be colored with water colors, oils, or spirit dyes in shellac or lacquer, and the outline can be "separated" on a contrast-infrared plate with hardly a trace of the color washes, no matter how concentrated the colors are. If desired, the plate-maker can make a positive from the infrared line negative and use it as a mask over the color-separation negatives to remove the record of the line drawing from the color plates. Mechanical drawings can be colored for the identification of parts and readily rephotographed by infrared when necessary.

Contrast-infrared plates are useful for photographing the black impression on subjects which have been printed in colors with

black, provided other infrared-absorbing pigments have not been used in any of the colors. This might be of assistance in printing new editions of maps, posters, and advertising material. In the reproduction of miniatures, portraits, or commercial photographs which have been colored with more or less transparent colors, the silver image can sometimes be separated by means of infrared. It should be borne in mind in this connection that iron double cyanide blues are often used in this kind of work because of their tinctorial strength. These pigments are opaque to the infrared. If photographs are specially colored for reproduction by this method, however, infrared-absorbing colors can be avoided.

Most paintings, including fine art works, even when not created specially for infrared photography, will give better black printers on infrared plates than by any other single exposure. In many cases the separation is complete, because iron blues are avoided for permanent painting by a number of artists. Those who are familiar with the requirements of the plate-making process can put black in a picture or design just where they want it to be used in the reproduction.

In Germany, Fröhlich²³ made a study of the characteristics of certain printers' colors in the infrared and obtained results similar to those of Murray. Some of his observations are of particular interest in that he made a series of photographs of colored wedges with increasing wavelengths. Some of the colors showed high absorption of the near infrared in the region 7,300–7,800 Å, but were completely transparent at longer wavelengths. He also studied the effect of the addition of infrared-absorbing pigments to transparent ones, and confirmed that the relative opacity of some colors is due to their content of small amounts of strongly absorbing colors. In connection with the increasing use of color transparencies on films and plates and of color photographic prints on paper as originals for reproduction by photoengraving, it should be realized that most of the dyes used are quite transparent to the infrared.

Some observations by Bittinger⁷ may be mentioned in connection with the separation by photographic means of two colors which are visually identical. He selected paints having prede-

terminated and known reflection characteristics and a spectral difference which was not apparent to the eye. Scenes were painted in these colors and illuminated with light of one color to produce a certain visual effect. By changing the spectral quality of the light in accordance with the known invisible spectral difference in the paints, he was able to produce an entirely different visual effect. For instance, in one example the painting shows a summer scene when viewed by white light and an entirely different winter scene when illuminated by red light. The spectral characteristics of the paints used by Bittinger were determined at the Bureau of Standards and are described in a paper by Priest.⁵⁴

This difference in the spectral characteristics of pigments and dyes which are identical visually is of importance in connection with the detection of camouflage. Obviously, for camouflage to be effective against the camera provided with plates sensitized to the infrared, as well as against the eye, it is necessary to select pigments which are visually identical and yet which photograph in equal tone values by infrared (see Chapter XIII). This limits very considerably the choice of paints available and requires special attention in the case of green pigments selected to represent the green leaves of trees and plants. For instance, many of the green pigments photograph as grey by infrared, whereas green leaves and grass reproduce as bright.

The spectral characteristics of pigments and other coloring materials used for special purposes are also dealt with to some extent in later sections of this chapter. Infrared plates giving both normal and high contrasts find application in the graphic arts. The plates of normal contrast are used for continuous-tone photographs. For direct-screen negatives and line negatives, the contrast variety is used. They also find application when a continuous tone subject must be greatly increased in contrast. Lenses should be checked to ensure that they give sharp focus in the infrared when focused visually. If they do not, special methods of focusing will have to be employed. With the apochromats and high-grade process lenses, good infrared focus can generally be expected, particularly as low apertures are commonly used. The relationship between focus and wavelength is discussed in Chapters II and XVI.

EXAMINATION OF PAINTINGS

In recent years the competition for possession of the old masters has developed to a pitch of high intensity. The result is that enormous sums of money are paid for the paintings and that an enticing field has been laid open for the fraudulent exploiter of imitations. It has been stated by Maximilian Toch,⁶⁷ a leading expert on the authenticity of works of art, that the number of pictures bought and sold, at one time or another, as Rembrandt's, for example, is six to ten times as great as the number that Rembrandt can have painted. In the case of other artists, there is a much larger discrepancy. For instance, of some two thousand attributed to Van Dyck, perhaps only seventy were executed by his hand. Modern painters have also been extensively copied, so that a wit was once let to observe that of 2,500 paintings done by Corot in his lifetime, 7,800 were to be found in America.

The two factors which are of prime importance in determining the value of a work of art are its rarity and the name of the painter. It is of paramount importance in the mind of the scrupulous owner or purchaser that the work under consideration be genuine. As a result of this, a number of first-class laboratories have been founded privately or by museums and art galleries, in which particular attention is paid to the study of the characteristics of the material and technique of famous painters. They have become very competent in distinguishing between authentic works and copies, although in many cases their task is becoming increasingly difficult, because the forger is adapting his methods to keep pace with the improvements in analytical technique.

Several methods are employed by the examiners of paintings, most of them having been developed since the beginning of the second decade of this century. One of the most successful of these consists in the microchemical examination of the pigments. The most thorough work in this field has been done by Laurie³⁴⁻³⁶ of Edinburgh. The method consists in removing a minute fragment from the surface of the picture by means of a borer made from a hypodermic needle and then subjecting the particle to a

series of microchemical tests in order to identify the pigments of which it consists.

Many owners of old paintings, the authenticity of which is open to question, have a feeling that chemical examination will damage a picture, even though the result may be invisible to them. They have, therefore, a preference for optical means of examination. Of these, the microscopic method has proved of particular value since it permits a study of the characteristic brush work of the painter, the cracks in oil paintings, and so on. Another method which has been much used consists in examining or photographing the fluorescence of the pigments induced by ultraviolet radiation. Most of the dark inorganic pigments do not exhibit this property, but the presence of organic lakes may be detected by their characteristic fluorescence. White pigments may also sometimes be differentiated in this manner. Results obtained with mixtures are more uncertain than those given by the pure pigments themselves, and the color of the fluorescence may be affected by the presence of traces of impurities. Further, the fluorescence of the surface varnish or the medium may also mask that of the pigments. For these reasons examination by ultraviolet is of value only in exceptional cases, although it is usually advisable to employ it as part of the routine.

Examination by means of X-ray photography is important in that it reveals the nature of the panels and the nails in the wood, the characteristics of the brush strokes, the distinction between old and fresh paint, and so on.

In relatively recent years, infrared photography has been added to these other scientific tests for distinguishing between true and false paintings. Its value depends on the varying extents to which pigments, medium, and varnish absorb infrared radiation. In 1934 Laurie³⁵ wrote that up until that time the infrared method had not proved of much value for distinguishing among pigments in a painting. On the other hand, he stated that the penetrating power of the rays had been effective in revealing the details of a signature of Rembrandt of an earlier period and thus helped to establish the approximate date of a picture.

Two years prior to this, Toch had become interested in the photography of pigments by infrared and reproduced photographs

made of Winsor and Newton color charts⁶⁵ in which the special absorption characteristics of the pigments were very apparent (see Murray and Wilhelm, p. 184). Toch has applied the infrared method with much success and has shown, for instance, that it can portray the original drawing of a master through overpainting of another. An example is that of a well-known Rembrandt, "Herman Doumer, the Gilder," in the Metropolitan Museum of Art in New York. It had been supposed that this painting was glazed or partly finished by other hands—Lievens, Drost, or some other. When this picture and a faithful copy were photographed by infrared the copy showed no brush marks while the photograph of the original showed definitely the characteristic brush marks and underpainting of Rembrandt^{29, 67, 68} (Figure 40). Many Rembrandts have been copied by competent students or forgers, and, since some of these are now masquerading as originals, infrared photography could be of value in revealing them. Toch has also mentioned the case of an alleged Velasquez, for which \$100,000 was paid, in which infrared photography revealed an underlying sketch which never would have been used by the purported painter.

Auerbach¹ cites an interesting example of the use of infrared photography in revealing a woodcut underlying a tempera painting in an illustration in a work printed by Verard in Paris in 1494. Since the tempera was opaque to infrared, the photograph was made through the back of the sheet, which was of vellum. The assumption that vellum, like human skin, might be transparent to infrared seemed to be justified, for a very good photograph was obtained. Auerbach also illustrated the use of infrared in revealing printing underlying the end paper in a copy of Mandeville's "Travels."

The infrared has been much used in the study of paintings by the Fogg Art Museum of Harvard University,^{20, 37} and by Henri Marceau,⁶⁰ of the Johnson collection of the Pennsylvania Museum of Art in Philadelphia. R. A. Lyon, of the former museum, has reported very satisfactory penetration by infrared of a heavy layer of discolored varnish overlying an ikon of a "Madonna and Child," plain rendering of restorations, and clear differentiation between real crackle and false crackle which had been introduced into the surface of a restoration. In a very important

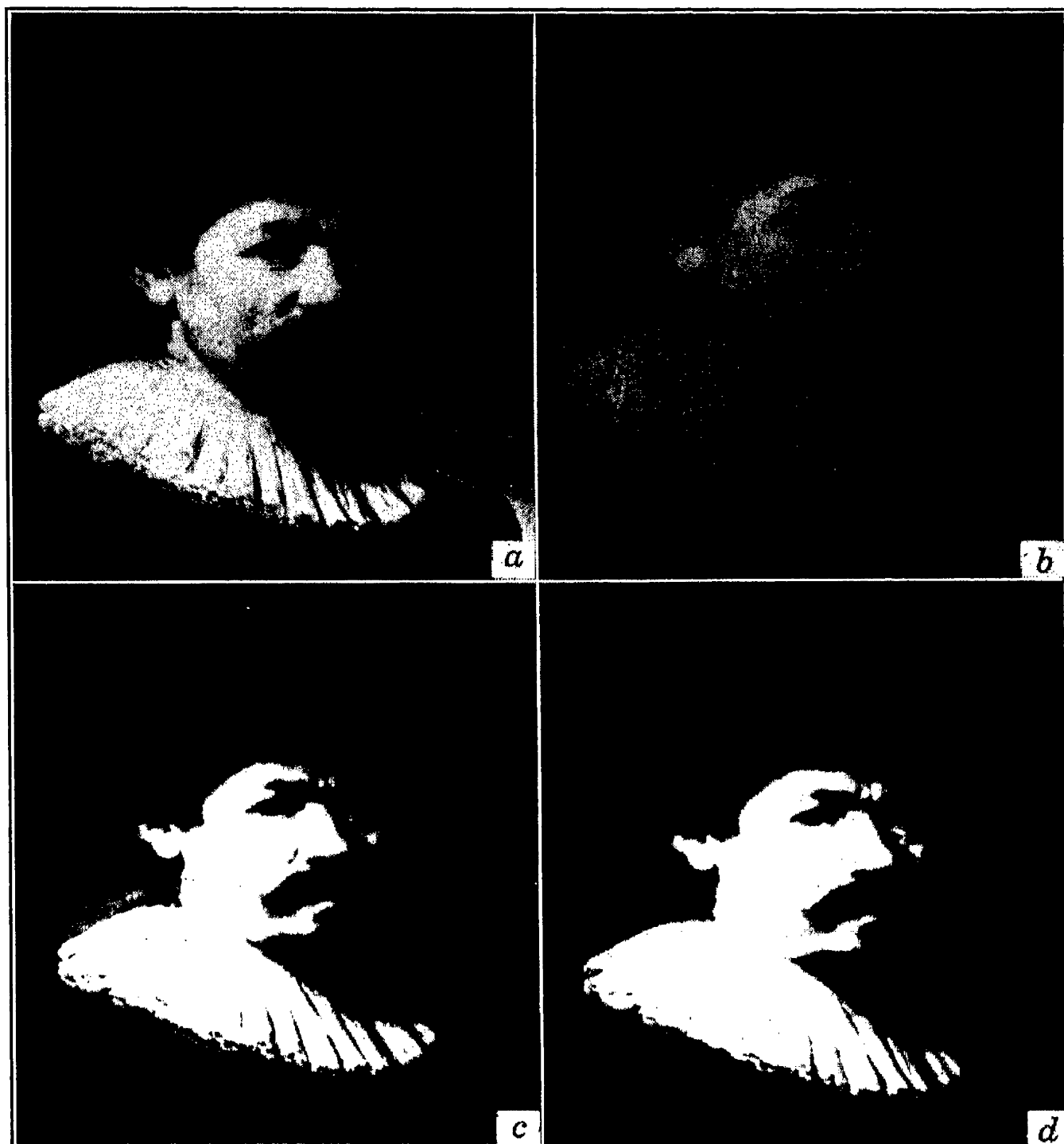


FIG. 40. Portion of painting called "Herman Doumer, the Gilder," by Rembrandt, in the Metropolitan Museum of Art, New York City. Photographed by Maximilian Toch.

- (a) Photograph of original on panchromatic film.
- (b) Photograph of original by infrared.
- (c) Photograph on orthochromatic film of faithful copy of original by Alvin Lee.
- (d) Photograph of Lee's copy by infrared.

(Courtesy Maximilian Toch)

study on the use of photographs in the identification of paintings, by Rosen and Marceau,⁶⁰ mention is made of the useful part served by the infrared when used in conjunction with other methods of examination.

In 1945 the Metropolitan Museum of Art in New York revealed the signature of Carpaccio on a painting in which the signature had been overpainted, and the signature of Mantegna later written in. Infrared was used to reveal the original.

Farnsworth²⁰ extended the work of Lyon³⁷ by studying the photographic infrared absorption of some common pigments, media, and their combinations. It was found that, in general, the infrared absorption of the media is low and that the absorption of the pure pigments is not very different from that of the paint films prepared from them. Anomalous results were shown with some samples of Cobalt Blue and Cobalt Violet, some showing almost no absorption while others showed almost complete absorption. In the case of the Cobalt Violet, the high absorption appeared to be associated with high cobalt phosphate content. The pigment absorption in the infrared is indicated in Table XIX for the range of pigments studied.

TABLE XIX

<i>I</i> <i>Slight or No</i> <i>Absorption</i>	<i>II</i> <i>About 25%</i> <i>Absorption</i>	<i>III</i> <i>About 50%</i> <i>Absorption</i>	<i>IV</i> <i>About 75%</i> <i>Absorption</i>	<i>V</i> <i>Complete or Almost</i> <i>Complete Absorption</i>
Barium sulphate	Alizarine Crimson	Dragon's Blood	Indian Red	Azurite
Cadmium Red (light)	Cadmium Orange	Ultramarine (artificial)	Indigo	Burnt Sienna
Chrome Yellow	Cadmium Red (deep)	Venetian Red	Raw Sienna	Burnt Umber
Cobalt Blue(?)	Carmine Lake		Terre Verte	Chrome Green
Hansa Yellow	Cerulean Blue			Cobalt Blue
Lithopone	Chromium oxide			Cobalt Violet (phosphate)
Madder Lake	Cobalt Green			Cupric carbonate
Orpiment	Cobalt Violet (arsenate)			Emerald Green
Smalt	Cobalt Yellow			Ivory Black
Titanox A	Gamboge			Lamp Black
White lead	Manganese Violet			Prussian Blue
Whiting	Red lead			Raw Umber
Yellow Lake	Strontium Yellow			Scheele's Green
Zinc White	{ Ultramarine Vermilion Zinc Yellow }			

A most comprehensive study of the optical and photographic properties of pigments was made by Vesce in connection with camouflage and is dealt with in some detail in Chapter XIII.

Toch^{66, 67} found that infrared is of relatively little use with a fresh painting, although it can be very effective with old ones. It penetrates the older paintings more readily, and Toch explained this as a result of the change in refractive index of the medium with age. That such a change does occur is clearly evident from experiments of Laurie.^{34, 36} The ease with which infrared is transmitted by a suspension of small solid particles in a transparent medium such as a paint is dependent on the size and nature of the particles and also on the relation between their refractive indices and that of the medium in which they are embedded. Increase in the refractive index of the oil in oil paintings has a marked effect upon the translucency of the pigments. For instance, a transparent blue, if applied in a thick layer, eventually turns black, and a thin layer of white lead, painted over black, gradually becomes transparent and allows the black to become visible again.

Laurie^{34, 36} published some interesting results on the rise in refractive index of a solid film of linseed oil with age. Starting from an initial value of 1.480, the refractive index rose to 1.512 in ten years. Study of a series of paintings ranging in age from a Sargent to an early fifteenth-century painting showed a progressive increase in refractive index of the medium from 1.514 to 1.590.

Pigments may be regarded as transparent bodies of high refractive index. The initial index of the medium is generally much lower than that of the pigment, and this results in scattering of light at the interface between the pigment and the medium, and so determines the apparent opacity and brilliancy of the paint. As the refractive index of the medium increases, so approaching that of the pigment, this scattering tends to decrease, and the apparent transparency of the paint increases. Another factor of importance is the wavelength of the light by which the painting is viewed. For a given difference of refractive index between pigment and medium, the transparency will be greater the longer the wavelength. These facts, coupled with the ob-

servation that the material of which many pigments are made is more transparent to infrared than to visible light, explain why infrared photography must be of some value for distinguishing between new and old paintings, and for revealing underpainting.

Rawlins of the National Gallery in London has published many papers on the examination of paintings,⁵⁵⁻⁵⁸ and a valuable survey of the work that has been done in the field from the physical aspect. In order to illustrate the way in which infrared photography can be used to study the techniques of the old masters, Rawlins shows photographs of the hands of Saint Francis from the great Demidoff Altarpiece, painted by Crivelli in 1476. The subsurface modeling becomes very evident in the infrared photograph, whereas it is suppressed in a panchromatic photograph. This undermodeling is a very significant part of the rendering of anatomical detail in the case of some artists, but it is not very obvious visually.

Rawlins designed a special camera for the infrared photography of paintings.⁵⁹ He considers that the camera should be all metal, with a parfocal lens to facilitate visual focusing. A fixed-focus camera is usually adequate, since most of the work is concerned with details, and the image may be of standard size.

The potential value of the infrared is considered to be greater than that of the ultraviolet in the examination of paintings, but Rawlins believes that the troubles are greater also. Perhaps the troubles of interpretation are, but experience in general indicates that the technique of ultraviolet photography is more difficult than that of infrared. A good point made by Rawlins is that the condition of the paint can be studied without the varnish layer being tampered with. Infrared photographs are valuable as evidence of the condition of the paint film before cleaning, and specially valuable as a safeguard against charges of having damaged a picture by cleaning it.

The importance of a knowledge of the optical constants of the constituents of paints was clearly recognized in a paper by Müller-Skjold and Schmitt.⁴⁶ These investigators reproduced four paintings in the interpretation of which infrared photography played a very decisive part. One of them was a Russian ikon in which the varnish had seriously yellowed with age, and its visual transparency had decreased. By infrared the picture

was reproduced with surprising clarity as a result of the higher transparency to infrared of the yellowed and partly destroyed varnish layer. Cracks in the surface showed up more clearly and the hardness of the contours was increased. In another case, infrared photographs clearly established restoration which was not visible to the eye. An example is given of a picture of the later baroque period, covered with a deteriorated varnish layer which permitted only a few details to be seen. An infrared photograph revealed new detail. In another instance, a badly deteriorated painting of the "Descent from the Cross," when photographed by infrared, revealed an entirely unsuspected portrait of a woman underlying it.

Some consideration has been given to the infrared transparency of pigments and dyes in other sections of this book, notably those dealing with the graphic arts and textile industries, documentary photography, camouflage, and light filters. However, the literature contains innumerable scattered references to the properties of large numbers of coloring matters, many of which have been brought together in such works of reference as the "International Critical Tables," "Tables Annuelles de Constantes et Données Numériques," and Landolt-Börnstein's "Tabellen." The interested reader should consult these works.

Attention should be drawn here to articles by Rzymkowski⁴² and Mitchell⁴³ applying specifically to the materials used in painting. Rzymkowski studied a large variety of chromium compounds and found that they practically all reflect infrared in the wavelength region from about 7,200 to 8,800 Å. This reflection is independent of the behavior in the visible part of the spectrum. A very few chromium salts, such as CrCl_3 , Cr_2S_3 , Cr_2O_3 , do not have the same high reflection in the infrared. These facts are significant, since many chromium compounds are used as pigments.

In his many important papers dealing with the characteristics of inks and pigments, Mitchell^{42, 43, 45} makes some observations which will be summarized here. He states that the yellow pigments used for paints and printing inks are all more or less transparent to the infrared; they include Cadmium Yellow, lead chromate, and Yellow Ochre. Orange antimony sulphide is transparent and the black modification fairly so. Of the red and red-

brown pigments, Alizarine Red, Scarlet Lake, Vermilion, Cadmium Red, and red lead are transparent. Indian Red is opaque, and Red Ochre and Raw and Burnt Sienna are transparent in very thin layers. Of the blue pigments, pure Ultramarine, Indigo, and Cobalt Blue are transparent while Prussian Blue and Cyanine Blue are opaque. Some commercial specimens of Ultramarine, however, are relatively opaque, probably owing to the presence of impurities. From an examination of some ancient Egyptian pigments it was found that certain of the yellows, Orpiment and two Yellow Ochres (18th dynasty), were transparent; Red Ochre was transparent in very thin layers, as were also Azurite and Egyptian Blue. A blue frit containing iron was opaque, and malachite was relatively opaque. Certain medieval pigments, Azurite, smalt, and Lapis Lazuli from manuscripts were all transparent to infrared. Mitchell also examined a number of the enamel pigments, and reference should be made to his publications, in which their characteristics are tabulated.

DOCUMENTARY PHOTOGRAPHY

Some of the most elegant applications of infrared photography are to be found in the examination of documents. The usual object of investigating a document is to determine the nature of the writing or printing which was originally on it.^{6, 25, 40} This may have been rendered illegible in a variety of ways. The document may have been charred in a fire, or deteriorated as a result of age or the accumulation of dirt; the writing may have been obliterated by application of dark ink by a censor, or overwritten by a forger; it may have been eliminated deliberately by bleaching or erasure, and the parts so eradicated may have been written over. In all these cases, photography by infrared has helped to reveal the original writing.

Several methods are available for the examiner of documents, and all of them have their particular application to special cases. They include chemical methods of identification of inks, and the like; photographic and photomicrographic methods, including the use of filters in photography by visible light; photography by reflected ultraviolet or of the fluorescence induced by it; and infrared photography.

It was not until the introduction of the modern type of infra-red-sensitive plates and films that infrared photography was applied to any serious extent in documentary examination. In 1932 attention was graphically drawn to its possibilities by the publication of infrared photographs of censored documents by Bendikson of the Huntington Library and Art Gallery at San Marino, Calif.³ The library possesses a number of volumes of Theodore de Bry's "*Collectiones Peregrinationum in Indiam Orientalem et Indiam Occidentalem*," 1590-1634. Some of these bear inscriptions indicating that they were expurgated by the censor for the Spanish Inquisition to conform with the "*Index Expurgatorius*." The library contains, in particular, certain volumes made up of pages detached from de Bry's works, every leaf bearing one or more passages in most cases completely obliterated. Photographs of these made by infrared almost completely eliminated the censorial deletion and clearly revealed the original printing. A pair of photographs of one of these passages is shown in Figure 41. One of the pictures is a photostat copy showing the passage as it appears to the eye, while the other is the infrared photograph.

The publication by Bendikson of a number of photographs of this type immediately led many others to study the application of infrared photography to the deciphering of altered documents. Clearly, the results obtained owed their success to the fact that the censorial ink was transparent to infrared, whereas the ink used in the underlying printed matter was opaque to it.

Erasures on documents are generally made either chemically or mechanically, and may be for some legitimate purpose or for forgery. Very often the erased portions are written over. A number of cases in which infrared photography has enabled such erasures to be deciphered have been mentioned by various people, and a number have come directly to the attention of the author. Some of the most interesting will be described here.

An example of the use of infrared in restoring writing removed by chemical means is shown in Figure 42. It was made by Waters⁷² of Syracuse, N. Y., and is reproduced by his permission. The upper picture is a regular photograph of part of a stock certificate showing how it appeared to the eye. The lower photograph is a reproduction of the same section made by in-

frared. In the original document there was a very slight difference in color where the ink eradicator had operated, but there was no trace of the writing. The infrared plate has restored the whole thing beyond any question. The black patches on the lower photograph were deliberately placed there to obscure part

tum curaturos sese, vt omnis tum carceris, tum accusationis, tum politici magistratus iuris per omnia securi essent, promittebant. ~~Causa autem, cur lesuita~~
~~tam serium & indefessum in ipsis persuadendis Anglis laborem ponerent, hac~~
~~principaliter erat: quod supra dictus lesuita Germanus clanculum & in priuato~~
~~ex illis elicuerat, quod ingentem pecuniaz vim eo secum aduexissent. Huic itaq;~~
~~prædæ captandæ inhiantes, ac velut ex alto insidiantes, ad rem suam faciendam~~
~~augendam uel hanc artem sibi palmariam esse præferant. Primum siquidem~~
~~& maximum istorum hominum votum est, pensius habere nihil quicquam vi-~~
~~piam, quam ordinis sui salutem, comoda, & incrementa satagere. Quocunq;~~
~~id verò vel modo vel arte fiat, parum ipsorum interit: modò rei certus prouen-~~
~~tus fiat. Et si verò Angli non semel huic illorum petitioni intrepidè refragaren-~~
~~tur, conditionem suam institutumque longè diuersum esse attestantes: nihilo~~

tum curaturos sese, vt omnis tum carceris, tum accusationis, tum politici magistratus iuris per omnia securi essent, promittebant. Causa autem, cur lesuita tam serium & indefessum in ipsis persuadendis Anglis laborem ponerent, hac principaliter erat: quod supra dictus lesuita Germanus clanculum & in priuato ex illis elicuerat, quod ingentem pecuniaz vim eo secum aduexissent. Huic itaq; prædæ captandæ inhiantes, ac velut ex alto insidiantes, ad rem suam faciendam augendam uel hanc artem sibi palmariam esse præferant. Primum siquidem *lesuita ordinis vniuersi.* & maximum istorum hominum votum est, pensius habere nihil quicquam vi-
 piam, quam ordinis sui salutem, comoda, & incrementa satagere. Quocunq; id verò vel modo vel arte fiat, parum ipsorum interit: modò rei certus prouentus fiat. Et si verò Angli non semel huic illorum petitioni intrepidè refragarentur, conditionem suam institutumque longè diuersum esse attestantes: nihilo

Fig. 41. Photographs of censored passage from de Bry's "Collectiones Peregrinationum" by visible light and infrared.

The upper photograph, made by visible light, shows the document as it appeared to the eye. The lower photograph was made by infrared and has completely revealed the printing underlying the censorial ink.

(Courtesy L. Bendikson)

of the names of the people concerned who are still living. In the original negative the names appear in full.

Waters⁷²⁻⁷⁵ has made a special study of the infrared photography of documents. He has shown that it may be impossible to predict whether infrared will reveal chemical erasures, since it will depend on the kind of ink and the type of bleach. The infrared can be satisfactory in the case of erased or faint pencil

writing, because graphite absorbs infrared completely. Clearly, the abrasive action of the eraser must not have been heavy enough to remove all the graphite.

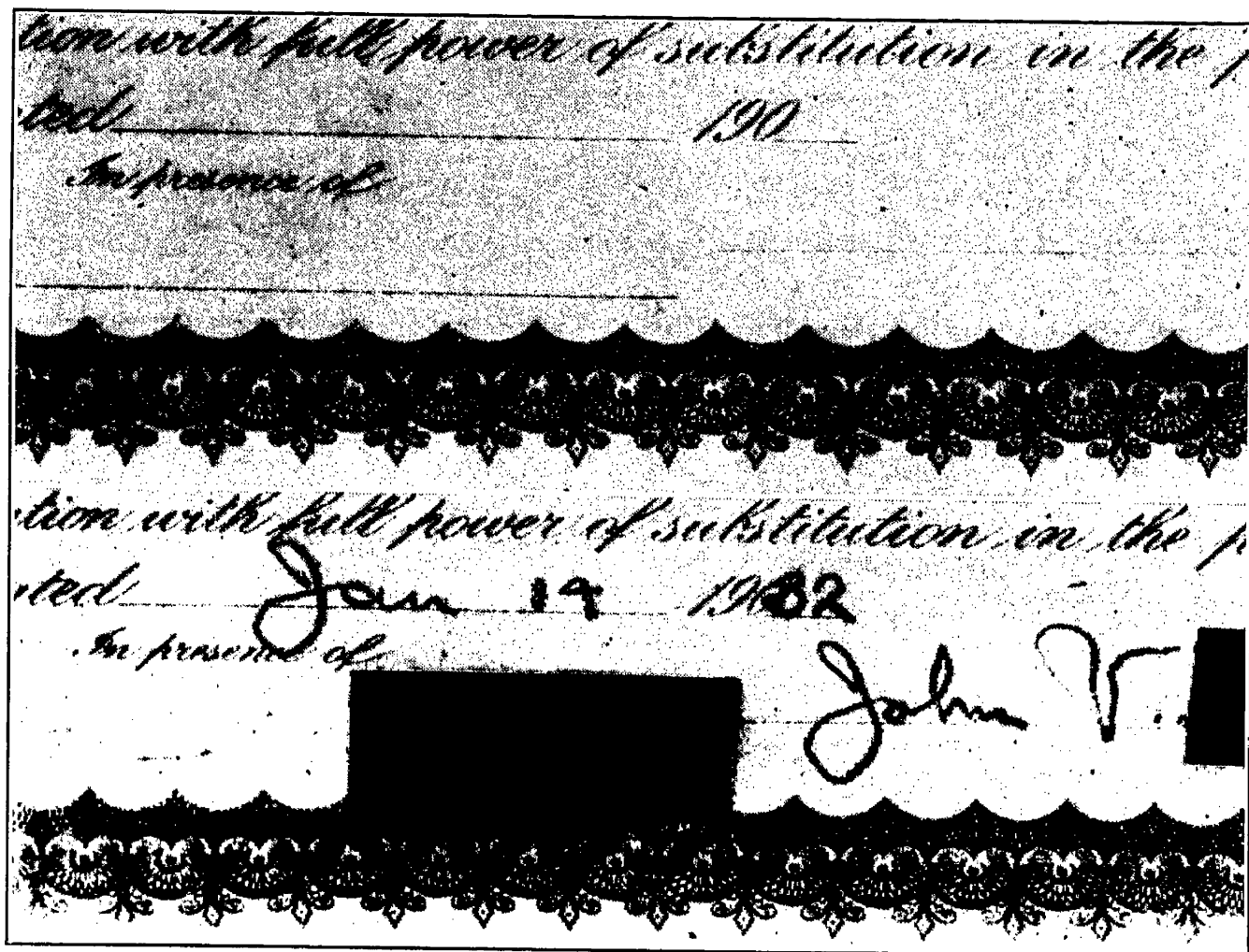


FIG. 42. Photographs of stock certificate showing restoration of chemically bleached writing by infrared.

The upper photograph shows the certificate as it appeared to the eye. The lower photograph was made by infrared and clearly reveals the original writing. The black patches were affixed to obscure the names of the parties, who are still living.

(Courtesy L. A. Waters)

Bendikson⁵ has described the use of infrared photography in revealing secret passages in certain eighteenth-century diplomatic missives. In one case which he mentions, the secret writing had been revealed by chemical means some 150 years ago. Since no fixative was used to give the message a permanent character, the chemical writing had disappeared almost completely in the

course of time. An infrared photograph made with oblique illumination showed it very clearly, when no results were obtained by the use of ultraviolet.

Mechanical erasure of writing may be intentional, or the result of handling the document over a long period of time. In both these instances, particles of the writing material are usually left embedded in the paper fibers, even though they may not be visible. They may often be shown up by means of the infrared. Oblique illumination is very often used to study documents from which writing has been removed mechanically. It takes advantage of any depressions in the paper which might result from pencil writing. Sometimes, however, the relief is not sufficient to permit the writing to be seen by the eye or in an ordinary photograph. If infrared photography is combined with flat oblique illumination, the results are very often greatly improved. A particularly interesting example of this method, also due to Waters, is shown in Figure 43. The writing had been in pencil on a card and was later erased, and the card was written over in ink. The pencil writing was not visible by any ordinary method of perception, although oblique lighting through a slit did show that there had been an erasure. The infrared revealed the pencil writing in full and led to the conviction of a criminal. For judicial reasons it is possible to reproduce only part of the card, but from this it will be obvious that the original writing is portrayed in surprising clarity. Quite a number of cases of this kind have been successfully photographed and admitted as evidence in the courts.

Other mechanical erasures which have been deciphered by the infrared include altered passports, insurance stamps from which the cancellation had been removed (Nickolls⁴⁹), parts of engineering drawings in ink on tracing cloth, an invisible worn label on a stolen money bag of leather (United States Federal Bureau of Investigation), and rubbed pencil drawings.

Interesting use for infrared photography was found at the British Museum³³ for deciphering very early Egyptian texts of about 1,200 B.C. The museum had 13 of these written on very dark brown leather. The black text could be distinguished very faintly and imperfectly, and the lettering was too weak and

broken to be deciphered. Although some improvement was made when panchromatic plates and red filters were used it was only by the use of infrared that the text was revealed with most satisfactory legibility in all 13 cases. Beardsley² has had excellent results with infrared photography in deciphering badly discolored papyri. Papyrus does not fluoresce to any appreciable extent,

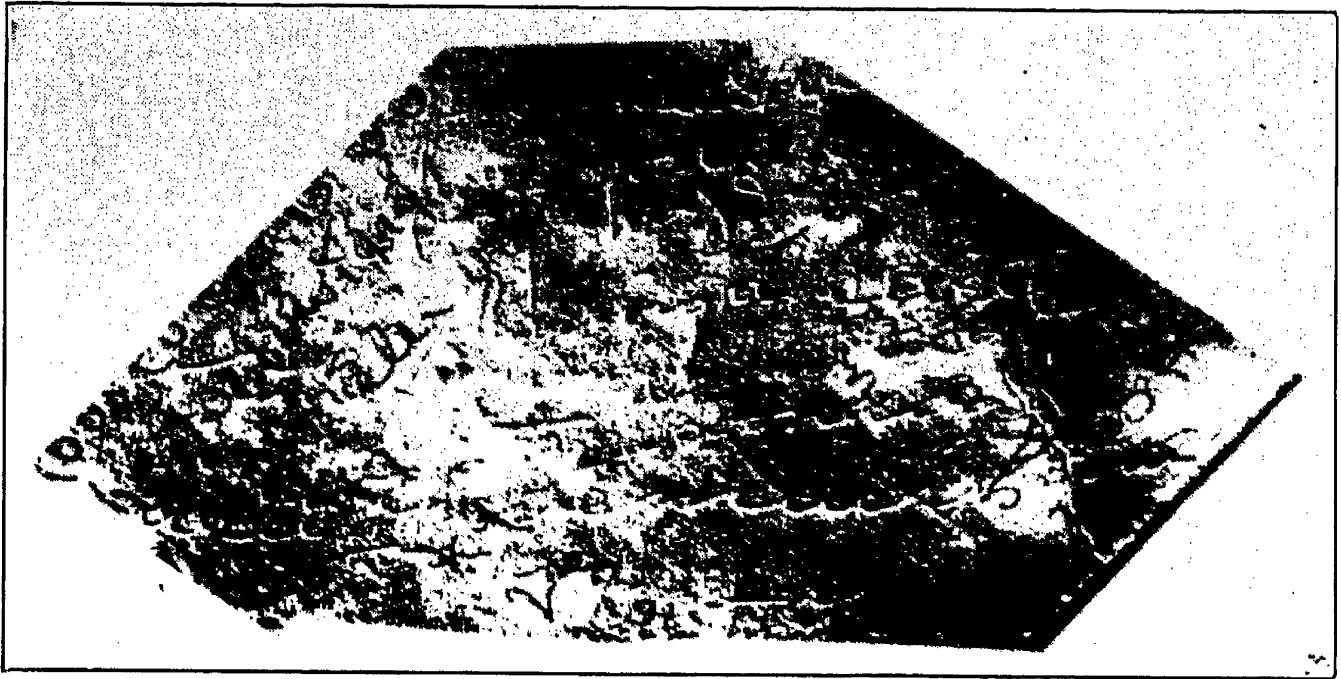


FIG. 43. Infrared photograph of portion of postcard showing restoration of erased pencil writing.

(Courtesy L. A. Waters)

so that photography by ultraviolet was of no value. On the other hand, infrared photography revealed the original writing perfectly.

Many other types of document rendered illegible by age or the accumulation of dirt have been interpreted successfully by the infrared. In one instance, the log from a wrecked airplane, obliterated by dirt and oil, was deciphered. Maps which have yellowed and faded with age, spotted and discolored engravings, dirty and aged photographs,⁷⁶ and even bleached and spoiled daguerreotypes⁶⁴ have been reproduced satisfactorily. It is claimed that brown foxing marks can be eliminated by infrared photography in copying engravings,¹⁸ and that infrared is of particular value in copying old maps on parchment and varnished.²⁷

Documents charred by fire have always proved very difficult to decipher. An elegant method worked out by the Bureau of Standards consists in placing the document in contact with a photographic plate in the dark for several weeks. When the plate is developed a negative image of the original writing may appear. The method is relatively uncertain but has proved of value in many instances. In the case of the charred papyri of Herculaneum, it has been found possible to reveal much of the original writing by special photographic technique designed to produce the maximum of contrast. In recent years, however, infrared photography has been of some use in retrieving texts apparently lost through charring of the paper. Bendikson⁴ applied the method successfully to documents charred in the fire which destroyed the capitol at Albany some years ago and caused serious losses to the New York State Library. If large portions are charred it may be necessary to use more than one plate, as a result of differences in the degree of carbonization and in the consequent density of the images. Infrared photographs have revealed original fingerprints on charred paper (see p. 212). Infrared photography does not provide an infallible means of restoring charred documents, and some examiners, including the Federal Bureau of Investigation, have reported only limited success. Much appears to depend on the degree of charring of the paper. However, positive results have been obtained in some cases, and the possibilities of the method cannot be ignored. Figure 44 shows an example of infrared photography applied to the deciphering of a charred engineering drawing.

It was pointed out earlier that Bendikson's success in deciphering the passages in de Bry's "Voyages" was due to the transparency of the censor's ink to the infrared. Clearly, if an ink which is opaque to the infrared is overwritten with another ink also opaque to it, infrared photography cannot disclose the underlying writing. Similarly, it will be of no help if both inks are quite transparent to the infrared, or if the lower ink is transparent to it and the upper ink is opaque. However, if of two inks which look equally black the upper is more transparent to infrared than the lower, infrared photography will be able to reveal the original writing. It follows, therefore, that a knowledge of the optical characteristics of inks in the infrared is a

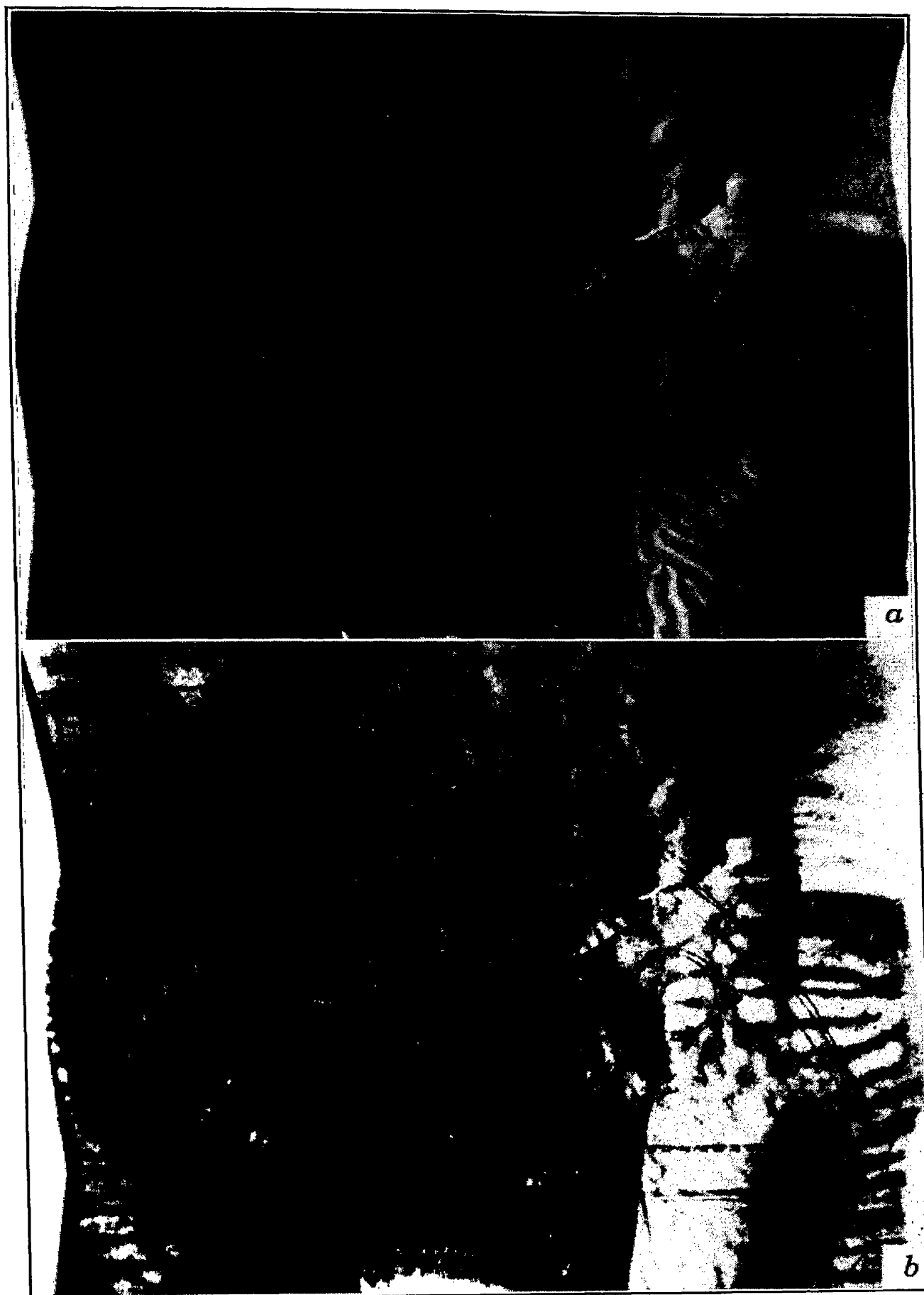


FIG. 44. Photographs of charred engineering sketch by (a) visible light and (b) infrared.

matter of considerable importance to the examiner of documents. This applies not only to overwriting, but to substitutions and additions made at a time subsequent to the original writing.

The most comprehensive study of the transparency of inks in the infrared has been made by Mitchell.^{42, 43, 45} The following observations are taken from his writings, which the reader should not fail to consult if he wishes the fullest details. Printing inks containing Lamp Black or Prussian Blue are relatively opaque to infrared and photograph as dark. The same applies to iron-gall inks, but most red, violet, or blue writing or typewriting inks are quite transparent. Aniline blue-black inks are usually transparent, while iron tannate or gallate inks and iron lignone sulphonate inks are more or less opaque, and the two classes thus may be distinguished by infrared photography. The provisional coloring matters—soluble blue and indigo—are practically transparent, and the relative opacity of blue-black iron-gall inks, which consist of a mixture of iron tannates and Aniline Blue, will increase with the proportion of the iron pigment. The relative proportions of blue dye and black pigment affect the results more than the absolute amount of black pigment. An important physical factor is the way in which, with some inks, there is a differential separation of the blue dye by the capillary action of the paper. Chrome logwood ink is somewhat opaque and osmium pyrogallate decidedly so. Mitchell points out that in the application of the infrared test to a document care must be taken to compare a large number of strokes of similar density, and blotted writing should be compared only with blotted writing. The reason for this lies in the fact that the blotted ink in such cases usually contains a relatively higher proportion of blue dye than the ink in unblotted writing. It also appears that there is little difference, if any, between infrared photographs of strokes in blue-black inks exposed on paper for periods ranging from 5 minutes to 14 days.

Systematic tests on the pigments used for drawing inks revealed great differences, ranging from nearly complete opacity in the case of the carbon blacks to transparency in the case of the vegetable lakes. The organic pigment Sepia is relatively opaque to the infrared. Aniline Black marking inks are more or less opaque, but there is appreciable difference in the degree

of opacity between markings made with two-solution inks and those with one-solution inks. The marks produced by silver marking inks tend to be less opaque than those from a two-solution aniline ink. The natural vegetable pigments of the Indian marking nut (*Semecarpus anacardium*) and of the berries of the Chinese varnish tree (*Phytolacca clavigera*) are relatively opaque.

The infrared method may be applied to the differentiation of the pigments in colored pencils and chalks. In the case of copying pencil pigments, the differences in transparency depend on the presence of graphite and its proportion relative to that of dye.

For fuller information on the infrared characteristics of inks and pigments, the reader should refer to the book and papers by Mitchell mentioned in the bibliography, as well as to the other sections in this chapter dealing with the examination of paintings, the graphic arts industry, and the textile industry.

CRIMINOLOGY

In the field of criminology, infrared photography has found many uses,^{16, 26, 28, 38, 49, 50} which include the following: detection and deciphering of erasures and forgeries; deciphering of charred documents, or those which have become illegible as a result of age or abuse; differentiation among inks, dyes, and pigments which are visually identical; distinguishing between cloths which are apparently identical, but which are differently dyed; detection of stains and irregularities on cloth; examination of cloth, fibers, and hair which are dyed too darkly to be easy of study by visible light; study of fingerprints; examination of the contents of sealed envelopes; detection of certain kinds of secret writing; detection and demonstration of bloodstains on cloth; determination of carbon monoxide impregnation of victims of gas poisoning; photography in the dark.

Most of these subjects are discussed in detail in the preceding sections of this chapter and in the chapters on medical infrared photography and infrared photomicrography, and the interested reader should refer to them. A few special cases are mentioned here.

In certain circumstances, it appears that bloodstains on dark cloth can be rendered visible in an infrared photograph. However, Mitchell states that in his experience it is possible for a bloodstain, especially one on a red cloth, to be plainly visible to the eye or to appear in an ordinary photograph, but to be invisible in an infrared photograph. He points out that the difficulty of contrast might sometimes be overcome by converting the iron of the hemoglobin into Prussian Blue, which is opaque to the infrared. On the other hand, Martin³⁸ obtained an infrared photograph of a bloodstain on dark blue cloth. It would seem that success in revealing bloodstains by infrared must depend on the condition of the blood, and on the region of the infrared used in making the photograph. The observations of Eggert and Merkelbach on the infrared characteristics of blood are of interest in this connection (see Chapter IX). Oxyhemoglobin is relatively transparent in the near infrared, but increases in opacity as the wavelength increases. Since bloodstains on cloth would be expected to be in the oxidized state, the chance of success in revealing them would thus be increased if the photograph were made by long-wavelength infrared. Obviously, it would be necessary for the dye of the cloth carrying the stain to photograph light in the infrared.

Jörg³⁰ reports instances of the revelation of tattooing by infrared photography, after it had been rendered invisible by artificial inflammation of the skin by ultraviolet and diathermy treatment.

Many of the products of combustion of black and smokeless powder are opaque to infrared. By the use of infrared photography, therefore, it has been found possible to show up smoke halo, powder residue, and contact ring in the case of bullet holes in cloth, even when the fabric is dark or bloodstained.^{38, 48, 71}

Paper is relatively transparent to infrared, and it is very often possible to take a photograph of a document within a closed envelope by placing it in contact with an infrared plate and exposing it to infrared radiation.⁵² A shadowgraph similar to an X-ray photograph can thus be obtained. If the contents of the envelope are not too bulky, and the ink on the document inside is opaque to infrared, and the envelope is not lined with carbon paper or some other material which will not allow infrared rays to pass, the writing on the document will show up in the photo-

graph. The violet paper lining commonly used in continental envelopes is quite transparent to the infrared.

Reference has been made earlier to the successful use of infrared photography in deciphering documents charred by fire. A particularly interesting example, shown in Figure 45, reveals three fingerprints which were not visible on the charred paper. The upper photograph shows the paper as it appeared to the eye, while that below is the infrared photograph. The specimen was prepared by E. V. Mullins, criminologist of Miami, Fla., and the photographs were made by H. C. Staehle, of the Kodak Research Laboratories. The charred paper was mounted in gelatin between two sheets of glass. The successful photograph was obtained only when the following conditions were observed: the lighting was very flat to suppress undesired detail in the charred paper, such as wrinkles; the exposure was confined to the infrared; a plate of high contrast was used; and the print was made on paper of the highest contrast available. The illuminator employed to give flat lighting consisted of a ring reflector of metal in which were mounted twenty 6-volt automobile headlight lamps connected in series. The specimen was photographed through the hole in the illuminator, which was 12 in. from the specimen. The lens was of 10-in. focal length, and the specimen was backed with photographic black paper for the infrared picture. A process type of infrared plate was used, and the print was made on paper of extreme contrast (Kodalith).

One application in the field of criminology which has been suggested often is the photography of criminals at work in the dark. It has been proposed, for example, to have a number of powerful sources of infrared radiation in a strong room or office, screened with a filter which is transparent to the infrared but opaque to visual light. Intruders are unconsciously made to operate a device which switches on the infrared and operates the shutter of a concealed camera, which takes a photograph of them. Alternatively, the source of infrared may be operating continuously, and the mechanism, set in action by the intruder, merely has to work the shutter of the camera. A very high wattage of lamps would be required to enable a sufficiently short exposure to be made, or a lamp of the Kodatron type or a flash lamp could be used (see Chapter XII).

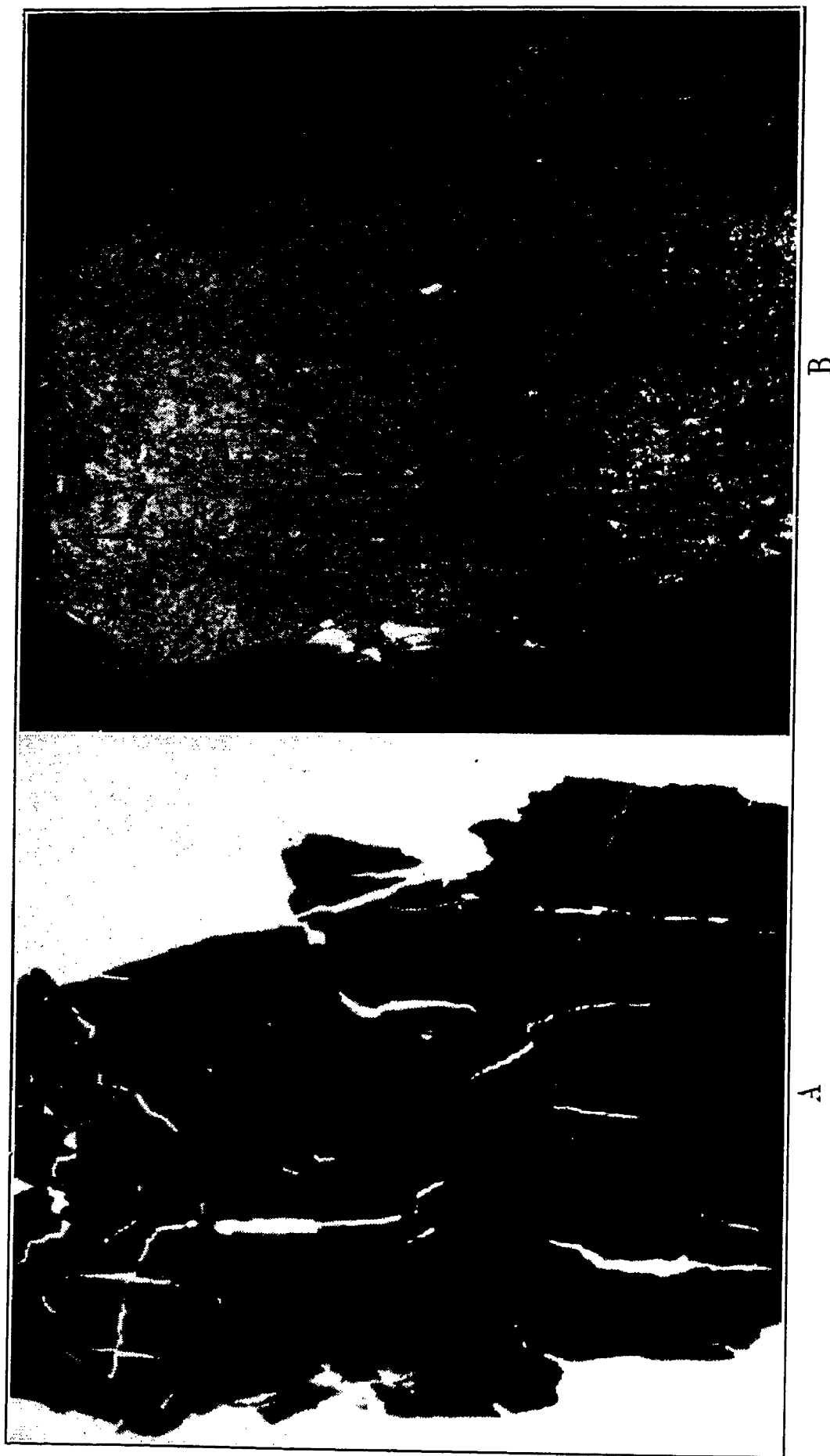


FIG. 45. Photographs of charred paper in which three fingerprints are revealed by infrared.

Photograph A shows the paper as it appeared to the eye, while B is the infrared photograph in which the fingerprints are clearly shown.

(Courtesy E. V. Mullins)

Bloch⁸ mentioned an instance in which an office was broken into, and a card, red on one side, was knocked on the floor by the intruder, who subsequently trod on it. Dirt was picked up from the carpet, giving a very faint impression of the sole of the boot. Photography by infrared accentuated strongly the parts carrying dust traces so that measurements could be made, and the boot was shown to correspond exactly with that of a suspect. The Federal Bureau of Investigation has shown an example of a Japanese fatigue uniform in which obliterated data were revealed by infrared.¹⁶

Mitchell⁴¹ has pointed out that it may be difficult to convince a court that an infrared photograph is entitled to any credence. It distorts tone values and may omit certain details which would appear in an ordinary picture. With the increasing admission of photographs as evidence, however, and a growing knowledge of how to interpret them, it is to be expected that in time they will be judged for their worth and not on the basis of their unusual appearance.

INCREASING CONTRAST PHOTOGRAPHICALLY

In the infrared photography of documents it frequently happens that the subject contrast is so low that it is difficult to distinguish it in the negative. Naturally, it should be made as high as possible by selection of photographic plates of adequate contrast, proper lighting of the subject, and development to the limit. If all these precautions are taken and the negative still shows too low contrast, other means are available by which an improvement can be made. It is sometimes found in the case of negatives which are so "thin" that no detail can be seen by transmitted light, that examination by reflected light against a dark background will show a faint image. If this is so, a copy negative should be made by mounting the negative in front of a hollow box lined with black velvet or coffin paper, illuminating it with one lamp placed well to the side, and photographing it from directly in front on a plate or film of high contrast. The so-called process plates and films, or preferably the photoengravers' films of the type of Kodalith, should be used. Contrast can be further increased by multiple printing from the negative thus obtained, or the original negative if it cannot be copied in

the manner described. A contact copy is made by printing onto a high-contrast film or plate—a contrast lantern plate is often satisfactory—and the positive so obtained is further printed onto a second sheet of the same material. Usually, the resulting negative will have adequate contrast, but if it does not the process may be repeated. This method of multiple printing has one disadvantage in that it tends to eliminate all gradation in the copy, resulting in hard dense lines with sharp edges. This is of no consequence in copying written or printed matter when it is merely desired to read the original material. Developers giving very high contrasts are preferred.

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Chapter IX

MEDICAL INFRARED PHOTOGRAPHY

In 1933 Professor Haxthausen,⁴¹ of the State Hospital of the University of Copenhagen, described the results of a study he had made of the application of infrared photography to dermatology. He argued very reasonably that, since infrared penetrated atmospheric haze and permitted photographs to be taken through it, it might allow photographs to be taken through the skin, which is also a medium that scatters light. His results unexpectedly showed that the veins underlying the skin could, in fact, be seen in an infrared photograph when they were not visible to the eye. Since that time a large number of such pictures have been made, and infrared photography has been applied to the study of other medical subjects.

That infrared rays could penetrate the skin was known before Haxthausen took his pictures, for they had been used in the practice of deep therapy, in which lamps of various kinds are used to warm up the tissues beneath the skin. Much study has been devoted to the selection of lamps most suited to this purpose.⁵⁸⁻⁶⁰ In a consideration of the principles involved in photography through the skin, therefore, much assistance can be obtained from an examination of the researches in the field of deep therapy. There are three main problems involved: the reflection, scattering, and transmission of radiation by the skin and the subcutaneous tissues; the spectral distribution of the radiation from sources which can be used to provide penetrating rays; and the spectral response of photographic plates and films which can be used for recording the reflected radiation.

TRANSMISSION AND REFLECTION OF INFRARED BY SKIN AND TISSUE

The reflection and transmission of radiation by the skin varies considerably in different parts of the spectrum and with different

parts of the body. Pigment, hair, and blood play an important part in determining the relative amounts of energy absorbed. Most of the investigations on the penetration of radiation into the body have dealt with the ultraviolet and visible light, in connection particularly with ultraviolet therapy. At the same time, the studies which have been made on the infrared are sufficient in number to give a clear picture of the conditions which ensure the most efficient use of sources emitting infrared radiation.

Light can pass through several centimeters of the human body. If the hand is held over a flashlight in a darkened room, it is seen to transmit visible light, tending toward yellow or red in color. This transmission of the visible is employed in the methods of transillumination which are used by the doctor in the study of the sinuses, the diagnosis of pathological conditions of the breast, and so on. Special lamps are available for this purpose, of which the Cutler lamp is probably the best known. It was even reported by Balderry and Ewald⁶ in 1924 that sunlight can penetrate the body to a depth of 25 cm.

Water forms the main constituent of all biological systems, and so its absorption characteristics are of importance. Radiation which cannot pass through a thin layer of water obviously cannot pass through body tissue. In the study of sources of radiation suitable for deep therapy, therefore, a number of investigators, notably Coblentz, Luckiesh,⁵⁸ and Forsythe and Christison,²⁸ have been guided by a study of the transmission characteristics of water.* The curves in Figure 46, taken from the paper by Forsythe and Christison, show the wavelength regions which are transmitted by layers of water 1 cm (curve *B*) and 1 mm thick (curve *A*). It may be seen that in a thickness of 1 cm, water is transparent to light of wavelengths in the visible spectral region (4,000–7,600 Å); it is only partly transparent in the near infrared region; it is opaque to radiations longer in wavelength than 14,000 Å in the infrared. In the layer only 1 mm thick, water is relatively transparent in the near infrared, shows a very strong absorption band at about 14,000 Å, and transmits in bands at about 17,000 Å and 22,500 Å. Although

* See also Chapter XVI.

it is not shown in the curves, there is complete absorption of radiation beyond this point out to about 80,000 Å. These long wavelengths cannot be recorded photographically and, consequently, are of no importance here.

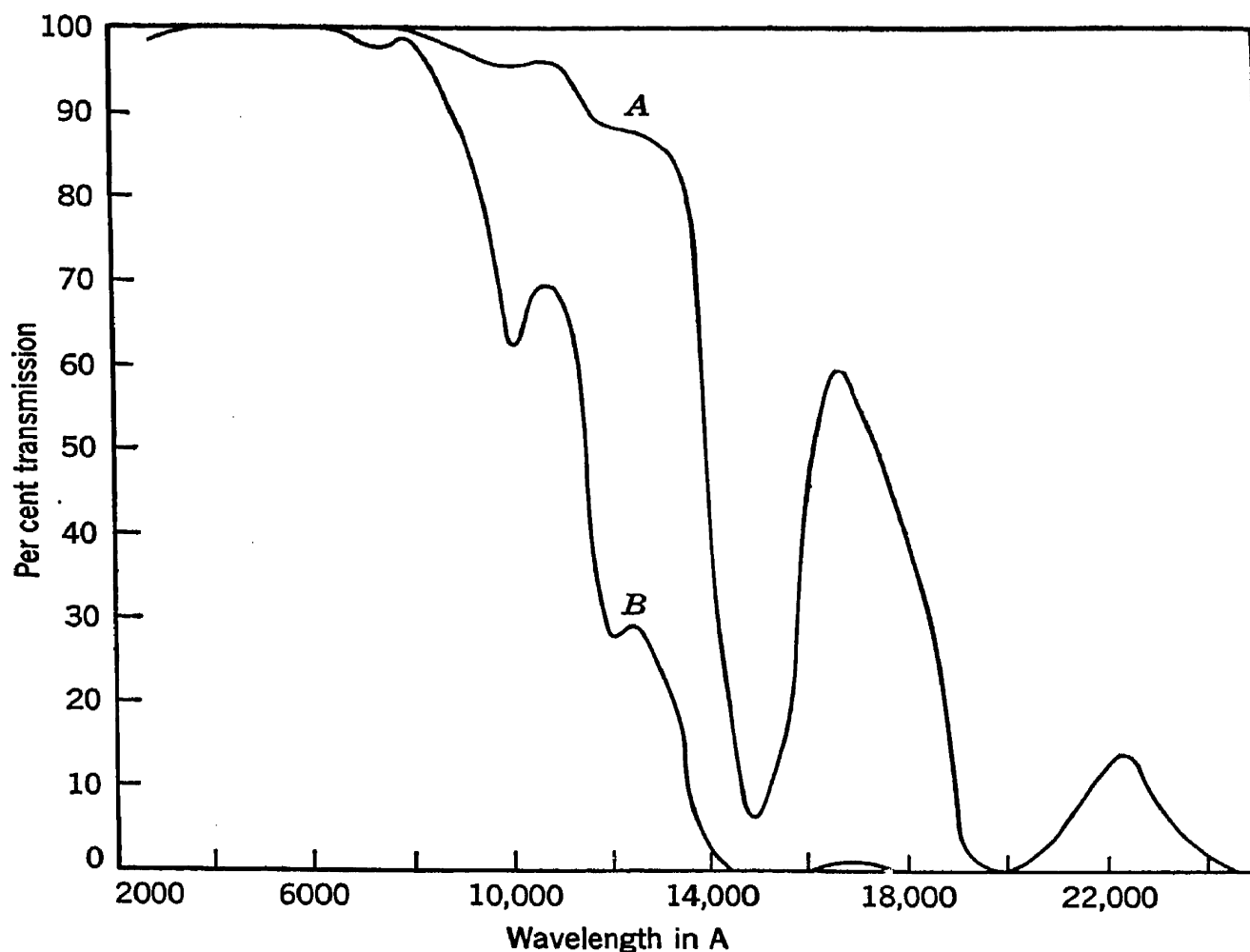


FIG. 46. Spectral transmission of water.

Curve A, transmission for a thickness of 1 mm.

Curve B, transmission for a thickness of 1 cm.

(From W. E. Forsythe and F. L. Christison)

Any source of infrared radiation which is to be used for heating the deep tissues of the body, or for photographing through the skin, should therefore emit a considerable proportion of its radiation in the near infrared at wavelengths shorter than 14,000 Å. This region can be recorded on infrared-sensitive photographic film.

In a series of papers, Dr. Carl Sonne^{52, 89-92} of the Finsen Light Institute of Copenhagen described some significant experiments

on the reflection, absorption, transmission, and heating effects of different parts of the spectrum of sunlight and certain artificial light sources. He stated that the near infrared penetrates the tissues for 2 or 3 cm, producing quite a marked increase of temperature, above the highest fever temperatures ever recorded. The skin is very opaque to infrared of long wavelength, which therefore is absorbed in the surface layer. Irradiation by it produces a painful and tingling sensation and significant increase in temperature of the skin. Results similar to those of Sonne were obtained by Loewy and Dorno.⁵⁵ They showed that the visible and short infrared rays of sunlight produced a temperature of 40° C at 2.5 cm below the skin, as compared with a maximum skin temperature of 38° C. On irradiation with long-wavelength infrared there was a temperature increase from within outward, whereas the short infrared penetrated and the temperature at the skin was lower than that in the subcutaneous layers. It is clear from these observations that the short-wavelength infrared penetrates some distance through the skin, whereas the long-wavelength infrared is mostly absorbed by the skin itself.

Following on the work of Sonne, Danforth¹⁷ and Cartwright¹³ measured the transmission of the tissue layers of the cheek, 5 mm thick. As instruments of measurement, both infrared-sensitive photographic plates and a vacuum thermocouple were used. By the photographic method, the transmission in the region of 8,600 Å was found to be about 14 per cent. With the vacuum thermocouple, the complete transmission curve was obtained for the range of wavelengths from 5,000 to 15,000 Å. The transmission increased to a maximum of 20 per cent at 11,500 Å. Beyond this point the transmission rapidly decreased, undoubtedly owing to the absorption by the water in the tissues. Cartwright's transmission curve¹³ is reproduced in Figure 47, curve *B*.

Sonne found the light reflected by the cheek to be about 34 per cent in the spectral region investigated by Cartwright. A correction for this was applied to Cartwright's curve by Forsythe and Christison,²⁸ who thus obtained the curve shown as *A* in Figure 47. The transmission factors given in these curves cannot be considered to be strictly correct, because no account appears to have been taken of the diffusion of radiation within the flesh.

However, the spectral characteristics of the transmission should be represented fairly well, indicating the limits of transmission and the position of the maximum.

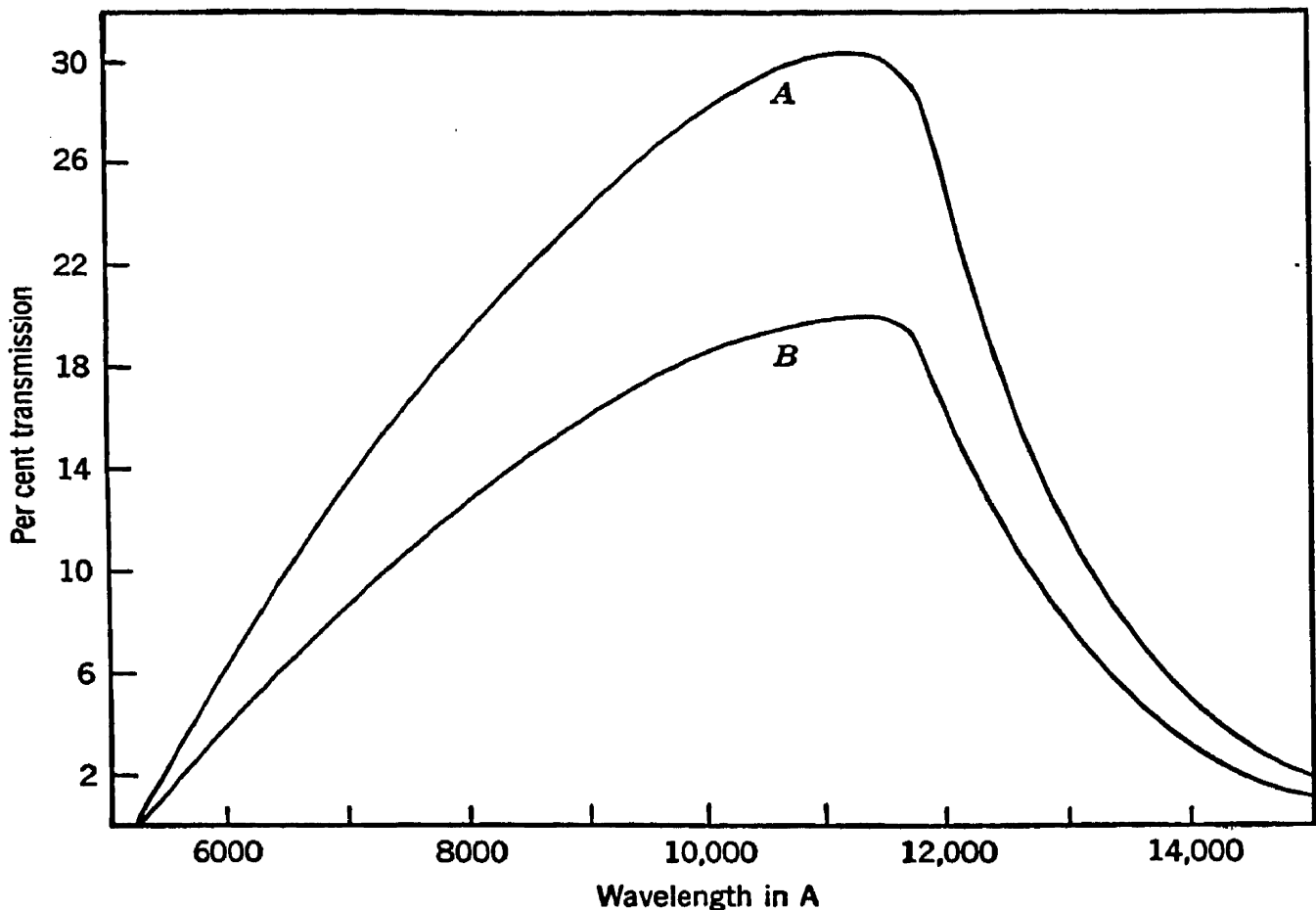


FIG. 47. Spectral-transmission curve of the human cheek for a thickness of 5 mm.

Curve *B*, results obtained by Cartwright without considering reflection from the surface.

Curve *A*, data from curve *B* corrected for 34 per cent reflection from the surface.

(From *W. E. Forsythe and F. L. Christison*)

Forsythe and Adams²⁷ published a table showing the absorption and transmission of radiation from different sources by different thicknesses of body tissue. The sources ranged in color temperature from 1,000° K to 5,400° K, that is, from a radiant heater to sunlight. The results indicated very clearly the greater penetration of the shorter wavelengths of the infrared.

The scattering of the light is an important factor which should be taken into account when measurements are made of the trans-

mission of the skin and tissue.⁵⁷ This has been overlooked by a number of investigators, and therefore their transmission values cannot always be taken as correct. In order to make reliable measurements, it is necessary to record not only the radiation directly transmitted by the sample, but also that diffused by scattering. This can be done either by placing the sample as close as possible to the measuring surface, such as a photographic plate, or else by completely diffusing the radiation before it falls on the sample. In addition to the radiation reflected or scattered by the skin and underlying tissues, there is also radiation emitted directly by the warm body itself.^{39, 40} It would not be expected that this would be recorded by the photographic method.

There is variation in the amount of fat present in different individuals and different parts of the body. This undoubtedly accounts partly for the fact that the power of radiation to penetrate the body depends on the subject and the position of the part investigated. Realizing this, Cartwright¹³ studied the properties of bacon fat and found that, although the transmission curve was similar in form to that found in the case of human tissues, the maximum transmission was at about 12,500 Å. For equal thicknesses, the bacon fat at this point let through some five times the amount of radiation that the cheek did at its point of maximum transmission at 11,500 Å. Using a photoelectric method, Heald⁴² found that infrared of wavelengths between 7,000 and 9,000 Å could pass completely through the wrist and forearm.

Gigon^{33, 34} and his collaborators studied the transmission of red and infrared radiations by more than 100 different animal organs. They found that the muscular system was quite transparent, but varied in transmission from animal to animal, being least in the case of the horse and greatest in the pig. The lungs have a very low transmission, while the brain, liver, kidney, and heart show a moderate degree of transparency. Further studies of importance on this problem have been made by Yamada,^{101, 102} Rücker,⁸⁶⁻⁸⁷ and Dent.¹⁹ A survey and bibliography are given in the article of Prát and Hrubý.⁸⁴

In infrared portraits of clean-shaven men the face often shows the appearance of having a stubbly beard. This has been observed even in photographs of Negroes in which the skin is

rendered as light and the beard as dark. That such photographs would resemble those of white men would be expected from the similarity of the reflection curves of white and of negro skin. The beard in a shaved face shows up owing to the transparency of the skin to the near infrared.

Much study has been devoted to the transmission by the skin alone. Clearly, rays which do not pass through this surface covering cannot be used for warming the tissues beneath it, nor for photographing through it. The external layers of the skin comprise the *epidermis*, while below this is a layer of connective tissue called the *corium*, which extends from the *epidermis* to the *subcutaneous tissue*. The external part of the *epidermis* is a horny layer known as the *stratum corneum*, while its inner layer is the *stratum germinativum*. These layers vary in their absorptive powers for radiation of different wavelengths.

The results of measurements of the transmission of the skin show much variation. In the ultraviolet region the absorption appears to be very high. Our chief concern here is with the infrared, but it will not be out of place to include some observations which have been made in the visible. Pearson and Gair⁷⁸ showed that in this region there was an increase in transmission with increasing wavelength in the case of specimens of human skin removed from the body, the ear of a live rabbit, and the *stratum corneum* detached by sunburn from the arm of a man. Similar results were obtained by Angus and Taylor,⁴ also for the *corneum*. Pearson and Norris⁷⁹ studied the transmission of the infrared from 6,000 to 50,000 Å using the *corneum* desquamated by sunburn from the outside of the calf of the leg of a white man. The transmission increased with wavelength to about 13,000 Å and then slowly dropped to 27,000 Å, beyond which it dropped suddenly to a sharp absorption band, having a maximum at 30,000–31,000 Å. Taylor⁹⁵ obtained similar results using the *corneum* peeled from the skin of a subject exposed to an arc lamp.

Bachem and Reed⁵ studied the transmission of various samples of skin out to 14,000 Å and recorded their results for the different layers. Their transmission curves showed that the *corium* and *epidermis* have their maximum transmission in the visible, and that it decreases with increasing wavelength. The full thickness of the skin, that is, 2 mm of the *epidermis* plus the *corium*,

has its maximum transmission in the near infrared between 7,500 and 9,000 Å, beyond which it falls with longer wavelengths. At the wavelength of maximum transmission, about 8,000 Å, the transmission is about 22 per cent. The conclusion drawn by Bachem and Reed is that the visible and near-infrared rays are absorbed strongly by the *corium* and subcutaneous layers. The far infrared has practically no penetrating power, being mostly absorbed by the *epidermis*.

Hoffman ⁴³ measured the transmission of the human hand and forearm and found it to be a maximum at the wavelength 7,000–8,000 Å.

The results obtained by various workers, and even the results of one observer, differ among themselves. This follows from the fact that differences in chemical composition, particularly pigment content and retained hemoglobin, relative thickness of the various layers, physical structure, and artifacts due to handling and treatment, all play a part in determining the transmission of the rays.

Hardy and his coworkers ³⁸⁻⁴⁰ at the Russell Sage Institute of Pathology in New York have published a series of papers on the thermal characteristics of the body, including the emission, reflection, and transmission of infrared radiation by the skin. The reflecting power of white and negro skin on the volar surface of the forearm was found to be about 20 per cent in the near infrared and to fall to about 5 per cent at 20,000 Å and beyond. It is interesting that the amount of reflection in the infrared is about the same for negro skin as it is for white skin. The observations on the penetration of skin about 1 mm thick showed extremely low penetrability even in the near infrared. About half the thickness of the specimens was actual skin, the rest being adherent subcutaneous tissue. The transmission at the maximum at about 12,500 Å was only about 1 per cent, and this dropped to a very low value at 30,000 Å. This low transmission does not agree with the findings of most other workers. Results obtained by Aldrich ² might appear to agree with those of Hardy and Muschenheim ^{38 40} in that Aldrich found the total transmission through skin 2 mm thick to be negligible. However, he used a source operated at 75–170° C in which the energy at 12,500 Å would be very low indeed. Spectral transmission data on the

epidermis of white and negro subjects showed increasing transmission to a maximum between 10,000 and 20,000 Å and a drop to a sharp minimum at 30,000 Å. Beyond this, the *corneum* still transmitted a large percentage of energy, while that through the *stratum germinativum* alone and through thicknesses containing both layers fell off markedly. The results agreed, in general, with the findings of Pearson and Norris.⁷⁹

The figures of Hardy and Muschenheim³⁹ relate to radiation directly transmitted and are not corrected for scattering. In a paper in 1936⁴⁰ they described further measurements of transmission, correcting for scattering. For a thickness of about 1 mm the direct transmission alone was only about 1 per cent, but when corrected for scattered radiation it was some 10 per cent at the wavelength of maximum transmission at 12,000 Å. This corrected value is very much less than that found by Cartwright for a specimen 5 mm thick. Living tissue is said to show considerably less transmission than dead, and, the longer the tissue has been dead, the greater is the transmission. A transmission curve of the human *corneum* alone, 0.03 mm thick, corrected for scattering, showed a transmission of about 50 per cent between 10,000 and 20,000 Å and a sharp drop to the absorption band at 30,000 Å. According to Hardy's figures, at the wavelength of maximum penetration at 12,000 Å, for dead tissue 21 per cent of the energy is reflected by the surface, 66 per cent penetrates the *corneum*, 50 per cent penetrates to the subcutaneous tissue, and 99 per cent is absorbed within 3 mm of the surface.

In 1927 Pauli and Ivančević⁷⁶ had studied the transmission of skin over the wavelength range 7,000–12,000 Å. The specimen was placed as close as possible to the thermopile so as to take into account the radiation scattered by the skin. The results showed that the human skin in a thickness of 2 mm has a very high transparency for the region 6,000–12,000 Å, the maximum being 47.6 per cent at 7,000–7,600 Å. The drop in the curve is slow on the long-wavelength side and so the transmission is still about 40 per cent at 9,000 Å. Rabbit skin is similarly very transparent, increasing progressively towards the infrared and reaching 68 per cent at about 9,000 Å. In the case of a rabbit's ear containing blood the transmission of white light was only about 4 per cent less than one without blood.

In the same year, Pauli ⁷⁵ found that the transparency of the skin for the visible and infrared could be increased by a superficial layer of oil or glycerin. The explanation of this increased transparency apparently lies in the elimination of the turbid layer in the outer cutis. Increases up to 70 per cent were obtained.

In 1931 Gaertner ³¹ studied the transmission of human skin in the region 3,000–20,000 Å. He used a thermopile and arranged the specimen so that light scattered by it was also measured. He found that in the region from 7,000 to 15,000 Å the transmission is at a maximum and only slightly dependent on the wavelength. In the case of specimens 0.8 mm thick the transmission at the maximum mounted to 50–60 per cent in some cases. Above 15,000 Å the transmission fell more rapidly than it did towards the violet. Between 7,000 and 15,000 Å various specimens behaved similarly.

The results obtained by Pauli and Ivančević and by Gaertner are apparently at considerable variance with those reported by Hardy and his collaborators. This is explained by these investigators on the basis that in the technique employed reradiation from the heated skin may have affected the thermopile, thus giving false values of transmission.

From the general survey of the published data on the transmission of infrared by the skin and underlying tissues, it thus appears that there is a maximum transmission in the region between 11,000 and 12,500 Å, immediately followed by a very strong absorption at about 14,000–15,000 Å. In the case of thin layers there is another transmission band around 17,000 Å, but this is scarcely noticeable when the specimen is over 2 mm thick. It seems that the transmission of dead skin is higher than that of corresponding live skin, and that, when the skin specimen is wet, the strong absorption bands of water are evident. The transmission spectra of thin layers of skin show absorption bands characteristic of the chemical structures present. The absorption band of thick specimens observed at about 14,000 Å is probably primarily due to water. In very thin layers, water also shows a transmission band at 17,500 Å, which is also found with thin specimens of skin. With thicker layers of water and of skin, this band disappears. There is strong absorption by the skin and

its component layers at about 30,000 Å. At the present time it is difficult to reconcile the varying figures for the transmission by the skin and subcutaneous layers published by different investigators.

SOURCES OF INFRARED *

The region with which we are concerned primarily is that which can be recorded on a photographic film or plate. However the results of different workers may vary as to the absolute values of transmission at different wavelengths, it appears certain that the best penetration of the skin and underlying tissues is achieved in the case of radiation in the near infrared at about 11,000–12,500 Å. It is clear, therefore, that, in order for photographs to be taken through the skin, the source of radiation selected should be very efficient in this region.

The most satisfactory sources for infrared photography through the skin are the incandescent tungsten-filament lamps of the types which are normally employed for photography by visible light. They emit their maximum energy in the desired spectral region with relatively high efficiency. As the temperature of a tungsten filament is raised, it passes from a dull red, barely visible at 500° C, to an approach to white at the temperature at which the tungsten melts at 3,370° C. This is due to the shift of the wavelength of maximum energy to shorter wavelengths with increasing temperature. With rise in temperature the total energy emitted per second also increases rapidly, as does also the height of the maximum in the curve. With the low-temperature radiators which are sometimes recommended for deep therapy, the maximum energy is in the spectral region of quite long wavelength in the infrared. The most efficient tungsten-filament lamps have their maximum in the region of 8,000–9,500 Å.

Table XX shows the transmission of radiation from different sources through different thicknesses of water and body tissue, and is taken from the paper by Forsythe and Christison.²⁸

Investigators such as Luckiesh and Forsythe and Christison have performed a very useful service in drawing attention to the absurdity of using low-temperature sources for deep therapy.

* See also Chapter VII.

These sources have their maximum energy at wavelengths which are absorbed by the surface layer of the skin. This is evident from the observation that radiant energy from a low-temperature source seems much hotter than the same amount of energy from

TABLE XX

TRANSMISSION OF RADIATION THROUGH WATER AND BODY TISSUE

	<i>Source of Radiation</i>			
	<i>Iron Heater, 1,000° K, Per Cent</i>	<i>Carbon Lamp, 2,150° K, Per Cent</i>	<i>Tungsten Lamp, 2,970° K, Per Cent</i>	<i>Sun, Per Cent</i>
<i>Flesh</i>				
1 mm	0.58	15.0	30.0	29.0
1 cm	0.02	0.9	1.9	2.3
<i>Water</i>				
1 mm	3.1	35.0	66.0	85.0
2 mm	1.4	28.0	59.0	81.0
5 mm	0.5	20.0	51.0	76.0
1 cm	0.25	15.0	43.0	71.0
5 cm	0.10	11.0	36.0	65.0
1 cm water and 1 mm flesh	....	....	19.0	....
1 cm water and 1 cm flesh	....	....	1.2	....

a high-temperature source. Forsythe and Christison give the following interesting illustration: If a nickel-plated electric flat iron operating at normal temperature is held within three or four inches of the face, the radiation from it seems very hot, much more so than the radiation from the sun in midsummer. Yet in midsummer, with the sun directly overhead, 1 sq cm of exposed surface receives radiant energy at a rate of about 107 milliwatts per square centimeter, whereas with the heated electric iron held within three or four inches from the face, the rate at which energy is received is only 70 to 80 milliwatts per square centimeter (see Chapter VII).

None of the low-temperature radiators which have been recommended so often for deep therapy is of practical use in infrared photography through the skin.⁵⁹ Even the carbon-filament lamp, which operates at a temperature of about 2,150° K, is of relatively low efficiency, and its wavelength of maximum emission is at about 14,000 Å.

Certain types of carbon-arc lamp are very efficient in the spectral region best suited to infrared photography through the skin, and these may be used if they are available. They are not so convenient, however, as the tungsten-filament lamps. The spectral emission characteristics of some of them are shown in Chapter VII. Another type of lamp which can be used with success is the flash bulb which contains aluminium foil or wire in an atmosphere of oxygen at low pressure. This lamp is very convenient when short exposures on restless or moving subjects are required, although there is the disadvantage that each lamp can be used only once. The spectral characteristics are somewhat similar to those of the overvoltaged type of tungsten lamp.

SUMMARY OF SOURCES OF INFRARED

To summarize, the following sources are best suited for medical infrared photography: tungsten-filament lamps of high efficiency, including overvoltaged lamps such as those known as Movie-floods and Photofloods, projector-type lamps, studio lamps, and high-wattage lamps for general illumination purposes; flash bulbs, such as those known as Photoflash and Superflash lamps, Sashalites, and Vacublitz lamps; carbon arcs with specially selected carbons.

STUDY OF THE SUPERFICIAL VENOUS SYSTEM BY INFRARED

Whatever may be the conclusions drawn by various investigators as to the transmission of radiation by the skin, a true evaluation of infrared photography as a means of penetrating the skin can best be obtained by actual tests. In his paper published in 1933 and mentioned at the beginning of this chapter, Haxthausen ⁴¹ described how he was able to show the subcutaneous venous system in infrared photographs which were made primarily for the study of skin diseases. He reproduced a series of illustrations, which compared ordinary photographs with those made by infrared using as light sources both the Nitrophot lamp and the Finsen-Reyn lamp. He stated that whereas in ordinary photographs and by direct observation it is possible to see only the very superficial small veins and the very large subcutaneous stems, in the infrared photograph there is a clear delineation of

all the small subcutaneous veins which form an anastomosis with the bigger stems. Haxthausen quite clearly stated that veins which cannot be seen by direct observation of the skin appear in infrared photographs and gave as examples photographs of the breasts and legs. Photographs of varices were made with very striking results. The bigger varices themselves do not show much more clearly than in ordinary photographs. In most cases, however, the infrared shows characteristic changes in the venous network. Instead of the thin relatively straight stems with their regular polygonal network found in normal *crura*, in varicose cases there are thickened sinuous curved stems often enlarged to small vein islands. These are doubtless a demonstration of the formation of varices in these relatively small veins, of which nothing could be known previously because they are invisible to the eye and are not shown in ordinary photographs.

At the beginning of 1934 Barker and Julin⁷ published some observations described before one of the staff meetings of the Mayo Clinic: "If one of the main venous trunks of the body is obstructed, there naturally is a congestion of its tributary veins and a slowing of the venous flow. This results in capillary congestion and a lowering of the oxygen content of the venous blood distal to the obstruction. The blood is darker and bluer than ordinary venous blood. In addition, a pressure load is thrown on the superficial collateral veins which become distended. Such veins, distended with abnormally blue blood, photograph considerably more vividly than normal cutaneous veins by the infrared method. This has been demonstrated in cases of obstruction of the femoral, subclavian, and portal veins and of the *vena cava*. It is questionable if veins can be recorded by infrared photography that cannot be seen with the naked eye. However, the veins stand out more vividly in the photograph than they do when viewed with the naked eye, and even slight unilateral differences in the prominence and blueness of the veins are well demonstrated. Further work will be necessary to determine whether this method of photography will have clinical value in the study and diagnosis of diseases of the veins."

About the same time Payne⁷⁷ published some photographs which showed that by using infrared plates it is possible to get photographic demonstrations of superficial veins which are not

recognizable clinically or by means of ordinary plates. At the time of writing, he found it very difficult to predict how any given cases would react to infrared photography but put forth the following tentative suggestions: (1) The method is more successful, in general, with women than in men, probably owing to their thinner skins; (2) normal subcutaneous veins do not show up at all sharply, but the method will demonstrate dilation or tortuosity of dermal or subcutaneous vessels; (3) very large tortuous varicose veins are not shown to the extent one would imagine, possibly owing to associated changes in the vein wall; (4) the method may have applications in connection with the prognosis after injection of varicose veins, and in the investigation of collateral venous circulations; (5) it may be used analytically in varicose ulcer cases; and (6) it may be capable of extension in conjunction with the use of intravenous dyes.

Massopust^{62, 69} was one of the first to make an extensive systematic study of medical infrared photography, and he published a number of interesting photographs of the upper and lower extremities, and the male and female thorax and abdomen. In these, the details of the subcutaneous venous system were shown up quite clearly, as in Figure 48, made by the Eastman Kodak Company. Jones⁴⁹ studied infrared photography in the hope that it would aid in the early recognition of collateral circulation in cases suspected of early portal obstruction. From the ten cases studied, he concluded that infrared photography offers a better means of demonstrating the collateral venous circulation in the abdominal wall than is afforded by any clinical method. He was inclined to agree with Payne⁷⁷ that in some cases the infrared technique will demonstrate veins that are not visible to the naked eye. At least he considered it an excellent means of recording abnormal degrees of superficial venous distension.

Interesting photographs have been made by The University Hospitals, Cleveland, Ohio,⁹⁷ showing marked dilation of the superficial veins of the breast associated, in one case, with a tumor, and in other cases, with chronic cardiac compression (Pick's disease). Photographs have also been published by Bloch, Rawling, Clark,¹⁴ Zimmermann,¹⁰⁴ and others.^{100, 105} In their paper on the transmission of infrared radiation through

skin, Hardy and Muschenheim⁴⁰ concluded that photography of the human body by infrared could yield detail not obtainable by ordinary photography, at least for structures within a few millimeters under the surface, although the detail might not be very sharp owing to scattering.



FIG. 48. Photographs of leg by visible light and infrared.

The location and extent of varicose veins are recorded in the infrared photograph, B, while other features, such as ischaemia, can be noted in the ordinary photograph, A.

In 1936 Massopust⁴⁵ published a photographic study of the changing pattern of the superficial veins in a case of human pregnancy. The infrared photographs formed a permanent record of the change in the size and pattern of the superficial vessels in the breasts and abdomen. A photograph of a patient taken 11 months after delivery showed that the superficial vessels had again resumed their normal appearance. There is a marked difference in the appearance of infrared photographs of primipara and multipara. Jaeger,⁴⁸ in his book on "*Ätiologie und Therapie der Varizen*," showed photographs of varices by visible and in-

frared and commented that the infrared plate showed all the veins lying under the skin to a degree which had never been suspected. Braga¹² of the Cancer Institute in Lisbon uses infrared photography to show the superficial venous network in cancer tumors. For the photography of superficial lesions, he preferred, in general, to work with panchromatic emulsions. When he desired to exaggerate the contrast of a red lesion on pink skin, he used orthochromatic films. In order to show up the superficial venous network in sarcomas and angisms, however, he used plates sensitive in the infrared out to 9,500 Å. In a discussion of the paper of Braga, Calzavara pointed out that this method had been used in the same study by Gosset, of the Salpêtrière, since 1923, and that the most satisfactory wavelength region was found to be 8,000 to 9,000 Å.

Infrared photography is employed at the present time as a routine method in many hospitals. Although the published statements concerning its value are at times at variance with one another, it has proved successful in so many cases as to justify the conclusion that it is a means of diagnosis and record which cannot be ignored. In many instances, infrared photographs certainly can show some superficial veins which are not discernible visually or in ordinary photographs. Distinct changes from the normal pattern have been recorded in connection with several diseases. Axillary thrombosis, cirrhosis, and some tumors, for instance, show a marked disturbance of the adjacent venous circulation. On the basis of this, it has been suggested that, in surgery for carcinoma of the breast, an infrared photograph made before the operation might reveal very valuable information.

PRACTICAL PHOTOGRAPHY OF THE SUPERFICIAL VENOUS SYSTEM

In the practical photography of the venous pattern, the principles employed do not differ in any way from those used in other infrared photography. The films should be sensitive somewhere in the region between about 7,000 and 12,000 Å. Actually, those sensitive between 8,000 and 9,000 Å will be used, because they are much more sensitive than those which respond to longer wavelengths, and there is scarcely any advantage to be gained by going to wavelengths longer than 9,000 Å.

The purpose of an infrared photograph is usually to record differences in reflectivity and transmission rather than form. Surface shadows and bright reflections from contrasty lighting must be avoided if the forms of the veins are to be depicted clearly against the diffuse background. The lights, therefore, should be flat and evenly distributed. If dark shadows cannot be avoided somewhere in the picture, special attention must be

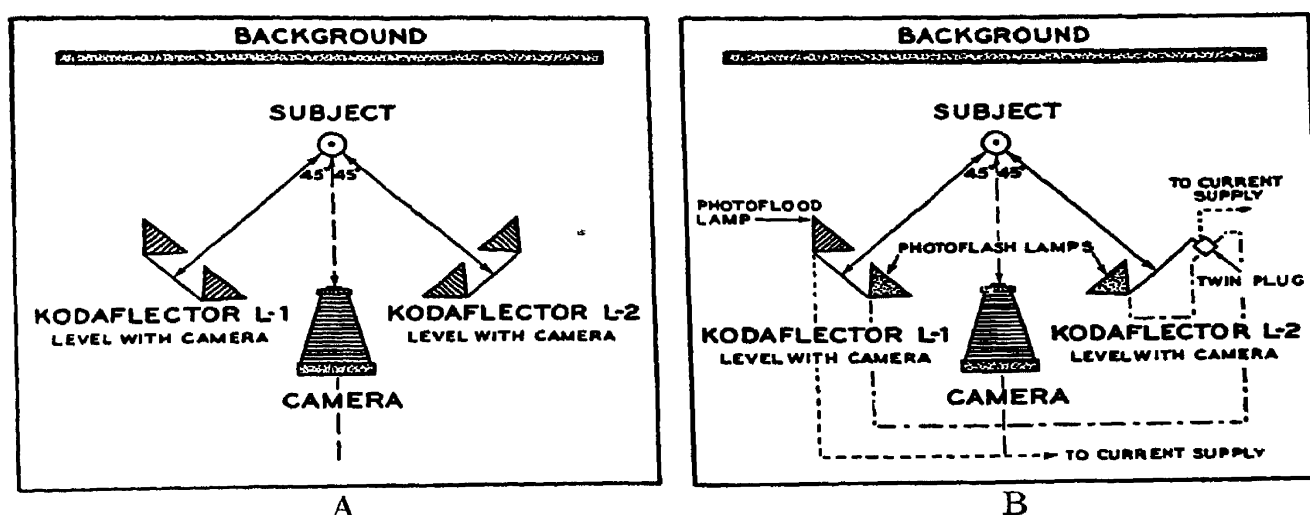


FIG. 49. Arrangement of lights and camera for medical infrared photography.

A shows the arrangement for infrared photography with Photoflood lamps. B shows the arrangement for infrared photography with two Photoflash lamps, with a Photoflood lamp being used for focusing.

directed to the lighting of the area to be studied. Photoflood or Photoflash lamps can be used; suitable arrangements are shown in Figure 49, for two pairs of Photofloods and two Photoflash lamps with a single Photoflood for focusing. The two flash lamps are set off simultaneously by pressing a snap switch on the socket into which a twin plug is fitted. If a single Photoflash lamp is used, it should be placed as near to the camera axis as possible, but better results are obtained with at least two lamps. Gibson³² has described in detail the technique of lighting of different regions of the body of characteristic shapes.

Exposure details for the arrangements shown in Figure 49 and taken from the "Kodak Data Book on Infrared" are shown in Table XXI.

TABLE XXI

EXPOSURE DATA FOR PHOTOFLOOD AND PHOTOFLASH LAMPS *

<i>Distance Lamps to Subject</i>	<i>Four No. 1 Photofloods † in Kodaflectors ‡</i>		<i>Two No. 22 Photo- flash Lamps in Kodaflectors</i>
	<i>Aperture</i>	<i>Time</i>	<i>Aperture</i>
3 ft	<i>f/16</i>	$\frac{1}{2}$ sec	<i>f/32</i>
	<i>f/32</i>	2 sec	
5 ft	<i>f/11</i>	$\frac{1}{2}$ sec	<i>f/22</i>
	<i>f/32</i>	4 sec	

* This table applies to Kodak Infrared Sheet Film, Kodak Infrared-Sensitive Plates, and Kodak Infrared Roll Film, used with A, G, or F filter. If the Wratten filter no. 70, 89, 88, or 87 is used, give double the exposure. No. 87 filter is to be preferred for documentary and clinical photography. For dark-colored subjects, give one lens opening larger.

† Two no. 2 Photofloods may be used in place of four no. 1 Photofloods.

‡ If Kodak Handy Reflectors are used, give double the exposure indicated above.

Since the exposures may be long, movement and breathing should be controlled. Removal of hair will aid in producing clear photographs, since profuse growths on the extremities, thorax, and abdomen obscure practically all the underlying skin surface.

INFRARED PHOTOGRAPHY OF GROSS SPECIMENS

Another field in which the infrared has been applied is the photography of injected gross specimens which later are to be cleared. This should be of interest to comparative anatomists, because the pictures furnish a check on the completeness of injection and offer interesting possibilities for the study of structure. They may be made by transmitted or reflected light, and a number of photographs obtained in both these ways have been exhibited by Massopust^{63, 64, 69} and Swindle.^{93, 94} If the conducting system of a fresh specimen is injected with India ink, which is opaque to the infrared, it can be shown very clearly in the infrared pictures when normal photography would reveal no detail. Sometimes the veins are injected with India ink and the arteries with red cinnabar (mercuric sulphide). If this is done, the veins appear black and the arteries white in an infrared photograph (Figure 50). Other color media might obviously be used for the same differentiation. The technique also has been

employed with success in the photomicrography of small specimens and sections, and is mentioned again in Chapter XI.

Zimmermann¹⁰⁴ showed photographs by visible and infrared of a stomach with a tumor (Ca). He pointed out that the tumor showed clearly in a plastic manner from the healthy tissue. Although the photograph by visible light showed the superficial

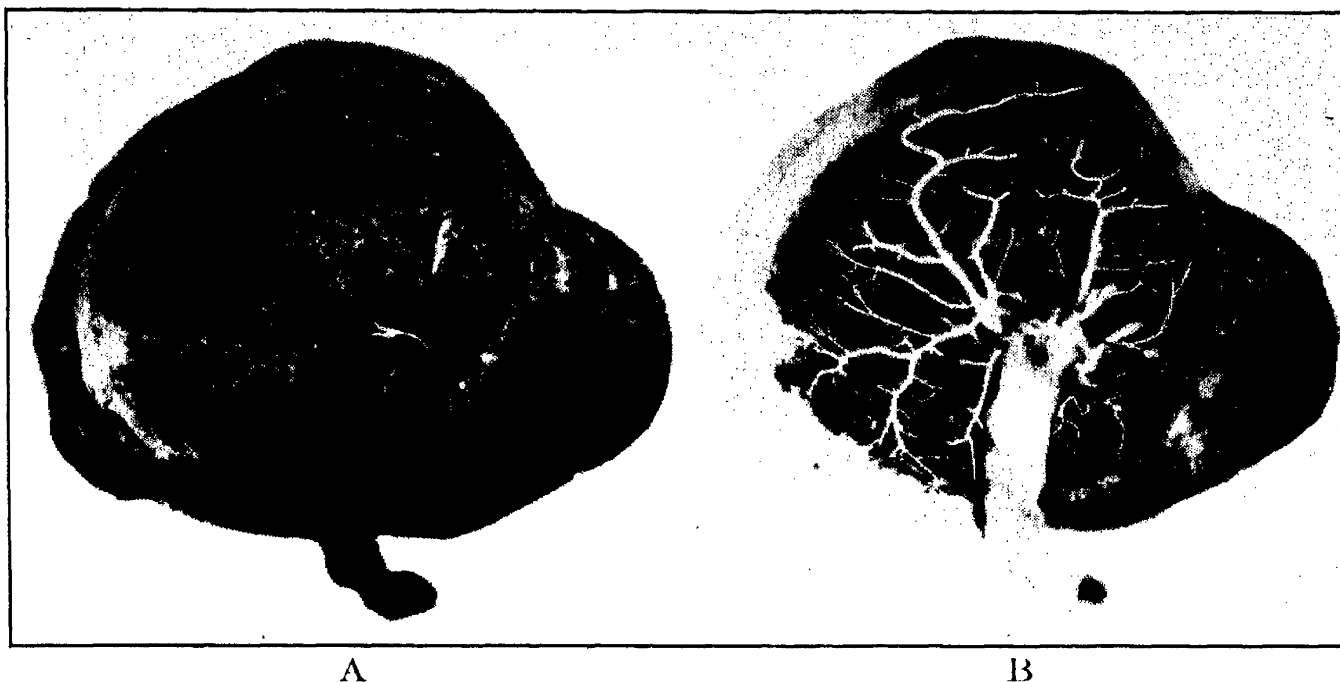


FIG. 50. Photographs of the human placenta by visible light and infrared. The arteries were injected with red cinnabar and the veins with a mixture of red cinnabar and black India ink. Photograph A was made on portrait film, and photograph B by infrared. The specimen was immersed in water.

(Courtesy L. Massopust)

details clearly, that by infrared showed a marked differentiation between the tumor and the surround, and also variations in red parts of the subject which could not be observed in the other photograph. He pointed out the advantages of the infrared in showing details which could not be seen in any other way.

Mills⁷² showed the superiority of infrared photography in demonstrating the presence of specific lesions in pathological specimens. He studied, in particular, the application of the method to show silicotic nodules in lung tissues. In the photographing of fixed lung specimens with panchromatic plates and films, the lung tissue is depicted clearly, but it is difficult to dis-

cern particular lesions of a silicotic type. The darker lesions are masked by the dominant reddish brown tone of the tissue. Infrared photographs reveal the presence of obscured lesions and show the difference between silicotic and other conditions that may exist in the lung tissue (Figure 51). Massopust also has employed infrared photography successfully in the study of silicotic and tubercular lungs.

The method of photography employed by Mills will serve as a general guide to the photography of other specimens and therefore is described in detail.

The specimen rests on a large sheet of plate glass, and the background placed beneath the glass is illuminated so as to give a diffused back lighting. Two 1,000-watt Mazda lamps in reflectors provide the illumination of the specimen itself; they are placed at 36 in. diagonally at each side and arranged to illuminate the specimen evenly. If there is interference from high lights on wet specimens, screens made of two thicknesses of tightly stretched cheesecloth are placed between the lights and the specimen, and close to the latter so that it is illuminated entirely by diffuse light. The camera is arranged vertically over the specimens. Under these conditions, if the Eastman Infrared-Sensitive plate Type-I-R and the Wratten no. 29 (F') filter on the lens are used, the exposure for an average specimen is about 15 seconds at $f/22$. Plates available at the present time are considerably faster, and exposures will therefore be correspondingly less.

Sometimes the specimens must be photographed in the glass jars in which they are mounted for display. In such cases a different arrangement must be used. The jar is placed against a light background, and the photograph is made with the camera in a horizontal position. Care must be taken to avoid interference due to irregularities in the glass of the jar, and in the cases where the fluid is discolored the exposure must usually be increased. In fact, exposures for specimens immersed in fluids in jars will generally be longer than those of specimens in the open.

In the photography of gross specimens, it is important to observe the bright reflections from the wet surfaces. In order to eliminate these it is necessary to use side lighting. In some



A

B

FIG. 51. Photographs of sectioned specimen of lungs by visible light and infrared.

A was made on panchromatic process film, and B by infrared.

(Courtesy Glenn Mills, School of Medicine, University of Colorado)

cases, Pola-screens will aid if the photographs are made by visible light, but it must be remembered that Pola-screens do not polarize the infrared, and therefore they are useless in infrared photography. Surface reflections can be avoided in some cases if the specimen is immersed in a liquid, usually water, in a cell with flat transparent sides.

INFRARED PHOTOGRAPHY OF THE EYE

A number of ophthalmologists have applied infrared photography to the study of the eye. The results are of such interest as to warrant serious consideration of the method as a general aid to this study, and more work in this field would be well justified.

The general characteristics of the eye as shown in infrared photographs were outlined clearly by Dekking,¹⁸ who appears to have been the first to apply the infrared method. In photographing the iris with infrared at a wavelength of about 8,100 Å, Dekking found that the dark-brown pigmented *irides* record lighter in tone than the blue *irides*. The deeply pigmented *trabeculae* register lighter than the other parts of the iris. In one case of iris bicolor, the brown fleck or segment registered much lighter than the rest of the iris, which is blue. If atrophy begins in the iris, resulting in destruction of the pigment and its replacement by greyish-white tissue, a photograph made by infrared shows this region of atrophy as darker than the normal tissue of the iris.

The reflection of infrared varies with the color of the eye pigments. The clear brown-pigmented portions of the anterior surface of the iris reflect the infrared strongly and are often recorded as light as the sclerotic coat. However, where the brown color is darkened by the pigment in the uvea showing through, the reflection of the infrared is less, and these parts appear darker in the photograph. The dark-brown pigmented margin of the pupil, which fades off in to the black of the pupil in an ordinary photograph and is hardly distinguishable in a color photograph, is easily seen in infrared pictures.

It may be inferred from this that the brownish-black pigments of the eye reflect infrared radiation to a greater extent than

visible radiation. It would seem, therefore, that the best way to record abnormalities of the pupil margin is by infrared photography. All the infrared studies of the eye made by Dekking led to the same conclusion. The human iris pigments strongly reflect the near infrared, instead of absorbing them in the same manner as they do visible light.

In 1933 in his first publication on infrared photography of the eye Dekking¹⁸ argued that, if the infrared can be used to penetrate atmospheric haze, it might be employed equally to examine the iris through an opaque cornea. As a test case, he selected a patient suffering from *keratitis parenchymatosa*, in whom frequently for a week at a time it was uncertain what was the condition of the iris, and whether *seclusio pupillae* was imminent. The result exceeded expectations. The turbidity of the *cornea*, which had completely prevented inspection of the interior of the eye, disappeared entirely in the infrared pictures and permitted a clear picture of the iris.

Pictures accompanying Dekking's article were of a case of *keratitis disciformis*, in which an iridectomy was performed to relieve the increased pressure. Although the wound healed normally and the pressure became normal, the *cornea* remained turbid after the operation, preventing a determination of the condition of the iris. An infrared photograph showed only a trace of the central infiltrate, whereas the cornea appeared clear, and the iris was revealed in all its detail.

It thus appears that the state of the pupil, the presence of synechiae, and the existence of defects in the iris, either congenital or operative, can be determined in an eye with a dense corneal opacity (Mann⁶¹). In addition to the illustrations of Dekking, other photographs have been published by Mann,⁶¹ and Feldman.²⁶

Kugelberg⁵¹ in 1934 showed many photographs of the fundus made by infrared and visible light and concluded that, although it is of considerable theoretical interest, infrared photography is of little practical aid in the diagnosis of conditions of the fundus. He found it difficult to obtain contrast and detail, and so the blood vessels were not sharply defined. All the normal retinal light reflexes are absent. The macula and parts of the retina

which are light in color do not show by infrared photography. Retinal hemorrhages cannot be discerned. It appears that the eye lacks not only the physiological but also the purely physical conditions to enable it to function as a satisfactory optical instrument in infrared radiation. Not only is there incomplete achromatism of the refracting media, but the back of the retina is highly reflecting to infrared. The normal fundus possesses no pigment which effectively absorbs infrared. In a discussion of Kugelberg's paper, Mann ⁶¹ states: "It is true that theoretically it would be possible to photograph the fundus through a cataractous lens and determine the presence of a pathological process in the choroid, retina, and optic nerve, since the infrared rays pass through an opaque lens the same as they do through the opaque cornea. However, even if one were able to overcome all the technical difficulties, and they are many, the information gleaned would be of questionable value since cloudings, haemorrhages and even changes in the papilla are not readily diagnosed and differentiated in the infrared photograph."

Infrared photography has been used in measuring the size of the pupil in studies of dark adaptation, since the infrared has no influence on the pupillary diameter. In an application of this, Nagel and Klughardt ⁷³ in 1936 published the results of measurements of the crepuscular pupil of the eye. The subjects were seated in front of a linen screen illuminated at the low brightness values desired, and, after adaptation, a source of infrared radiation was switched on and photographs were made on infrared-sensitive plates. The results showed that the method was satisfactory for measuring the pupillary diameter at very low brightness values. Gullberg, Olmsted, and Wagman ³⁷ used infrared photography to study the rate of change of the pupil diameter during dark adaptation, and two of these workers ⁹⁹ also used it to study the relationship between wavelength and pupil diameter at low intensities.

In general, it appears that in ophthalmology infrared photography is important for the study of the anterior portion of the globe, especially in giving an idea of the contour of the pupil and its size, shape, and position through an opaque cornea. It is also of value in the measurement of the size of the pupil in studies of dark adaptation.

PRACTICAL EXPOSURES ON THE EYE

The plates mentioned in the following are those actually used by the experimenters. At the present time the much more sensitive infrared sheet films would be used.

Dekking's pictures¹⁸ were taken at a magnification of three, with the radiation from a 15-volt 50-ampere Philips Cinelamp concentrated on the eye with both a spherical and a parabolic mirror. The light was filtered before it entered the eye by means of an Agfa no. 83 filter. An Agfa infrared plate R810 was used with an exposure of one-tenth second at $f/9$.

Mann⁶¹ pointed out that any camera suitable for the external photography of the eye could be employed. He found the stereoscopic anterior segment camera of Bausch and Lomb to be satisfactory. The Wratten filter no. 25 was employed, with Eastman Infrared-Sensitive plates Type 1-R. The exposure was about four times that required with supersensitive panchromatic film and the same camera and illumination. Feldman²⁶ used a Druener stereoscopic camera, with the lower power of the slit lamp at $f/5.5$ as the lens, and a 100-watt Photoflood lamp. With the Eastman Infrared-Sensitive plate Type 1-R and the Wratten no. 25 filter, the exposure was about 8 seconds. Correction of focus was achieved by focusing visually and then pushing back the camera $\frac{1}{200}$ of the distance.

For photography of the fundus Kugelberg⁵¹ employed the usual Nordensen fundus camera, with Ilford infrared plates and the Ilford infrared filter, and an exposure of one tenth of a second. In order to obtain a sharp infrared picture the camera bellows had to be extended 6 mm beyond that required for good focus in the visible.

For photography of the pupil in studies of dark adaptation, Feldman²⁶ had an ordinary 5 x 7 in. camera, with an $f/4.5$ lens. Illumination was provided by two 1,000-watt floodlights, one on each side at 3 ft from the subject. Eastman Infrared-Sensitive plates, Type 1-R, and a Wratten no. 25 filter were used. The exposure is not given.

Nagel and Klughardt⁷³ used two 500-watt lamps in lamp-houses with condensers, and in front of the condensers were Agfa infrared filters and diffusing glass. The lamp-houses were placed

right and left of the head of the subject to avoid interference with the visual field. With Agfa infrared plates 810 and an aperture of $f/4.5$, the exposure was about half a minute.

DERMATOLOGY

The earliest use of infrared photography in the medical field was in the study of affections of the skin. It was as a result of this that Haxthausen made the discovery that the subcutaneous venous system can be made visible in infrared photographs. Haxthausen,⁴¹ Massopust,⁶² Zimmermann,¹⁰⁴ and others have shown that, in the case of skin affections in which the lesions are rather deep seated, infrared photography provides a means of studying the progress of healing beneath the superficial scab, as well as the condition of the subcutaneous veins. This is important in that the surface characteristics provide little guide. In the case of the superficial skin affections, such as *psoriasis*, infrared photographs are of little value. The same applies to superficial pigmentary changes. In cases of *eczema*, the exterior eczematic appearance does not show in the infrared photograph, whereas the underlying varicose veins which usually accompany this condition are rendered clearly. In *lupus* cases under treatment with ultraviolet radiation, the whole of the lesion is covered with a scab, and it is impossible to see how clearance is going on. The infrared rays, however, ignore the scab, so to speak, and present a clear picture of the healed areas.

TRANSILLUMINATION

The relative transparency of animal tissues to visible light has permitted the development of the technique of diagnosis by transillumination. In this, the part of the body under examination is viewed by placing a concentrated bright light behind it. The method has been used in the examination of the anterior nasal sinuses, but has found particular application in the examination of the breast. This has been facilitated by the development of special water-cooled lamps, such as the Cutler lamp, so designed that they may be used with the minimum of discomfort to the patient. Transillumination shows up variations of density, thus permitting distinction between, say, a clear fluid cyst and a solid tumor.

In view of the higher transparency of the flesh to infrared, it would appear that infrared photography might give results showing superiority over visual examination. There has been very little work done along these lines.

Some work has been done on the photography of gross and photomicrographic specimens by transmitted infrared. For instance, Massopust⁶³ reproduced photographs of the chick and rabbit embryos stained with carmine, and the pronghorn antelope heart partially cleared and injected with India ink, in which great improvement in detail and contrast resulted from transillumination with infrared as compared with visible light. Plotnikow and his collaborators^{16, 20, 80-83} have made a study of the scattering of light and infrared by tissues and organs, from which they conclude that opacity exhibited by such bodies may be occasioned not only by reflection and absorption but also by complete internal scattering. This scattering plays an important part in decreasing the rendering of detail by transillumination in many instances, as shown by Eggert²² in the case of a mouse, and by Clark¹⁴ in the case of the hand. The degree of scattering, however, varies with the structure of the tissues and organs, and it can be concluded that, in the case of those bodies which exhibit it to a relatively low degree, infrared photography by transillumination may lead to records of value. In making such photographs of thick specimens it is often impossible to see any of the desired detail on the focusing screen of the camera, and it may be necessary, therefore, to make a series of photographs, focusing at different depths in the subject.

In 1937 Plotnikow⁸² reported that it was possible to reveal the blood vessels in a transilluminated hand by deliberately focusing on a definite plane in the depth of the tissues. Satisfactory photographs of the transilluminated face were also obtained by enclosing a light source in the mouth (see also Chapter XII).

SIMULTANEOUS INFRARED AND X-RAY PHOTOGRAPHY

Massopust sometimes employed a mixture of infrared and visible light in the study of gross specimens and in photomicrography. He has also made interesting pictures using a combination of infrared and X-ray photography.⁶⁶ In the case of some

objects, such as the moth and the frog, in which certain surface markings and structural details are not rendered in a normal radiograph owing to their high transparency, it is possible to show the details in an infrared photograph made by transillumination. If such an infrared photograph is made simultaneously with an X-ray photograph, the radiographic structure and the detail in the transparent portions may be recorded on one film. The object is placed on the emulsion surface of the film which lies on the bottom of a lead-lined lighttight box. In the upper surface of the box is a window consisting of a sheet of the Wratten filter no. 87, which is opaque to visible light, but freely transparent to the infrared and X rays. Exposure to the light from an electric lamp suspended over the box gives a photograph by infrared alone. If the exposure is made simultaneously to infrared and X rays, the combination photograph shows up the detail due to exposure to both sources.

It would appear that the results are similar to those which are obtained in radiography with very soft X rays, sometimes called grenz rays. Special apparatus is required for this work, however, and it might be well worth trying the method of Massopust when only normal radiographic apparatus is available.

INFRARED PHOTOGRAPHY AND THE BLOOD

In 1935 Eggert^{24, 30} published some data showing the behavior of various kinds of blood in the near infrared. In order to test their transparency, he photographed printed matter through glass cells containing them, and selected three wavelength regions between 7,200 and 10,000 Å. Reduced blood, carbon monoxide-containing blood, oxidized blood, and regenerated blood obtained by passing air through blood saturated with carbon monoxide all photographed as dark by visible light. In the infrared, the regenerated oxyhemoglobin and the carboxyhemoglobin were very transparent, while reduced hemoglobin was opaque in the shorter wavelengths of the infrared and increased in transparency with increasing wavelength. Oxyhemoglobin increased markedly in opacity as the wavelength increased, although it was quite transparent to the shortest infrared.

Eggert used these properties for the qualitative detection of carbon monoxide poisoning. If a drop of blood poisoned with carbon monoxide is photographed by infrared on a glass slide next to a drop of healthy blood, it will appear transparent while the healthy blood will appear dark. Eggert published absorption curves of the blood used in his experiments, and they substantiated the photographic findings. His work was extended further by Merkelbach⁷¹ who confirmed the strong absorption band of oxyhemoglobin with its peak just beyond 9,000 Å and the absence of such absorption in the case of carboxyhemoglobin.

The study was resumed by Horecker and his collaborators^{3, 44, 45} who worked out a photoelectric spectrophotometric method for determining methemoglobin, carboxyhemoglobin, and total hemoglobin in blood, using the infrared absorption characteristics. They have published the spectral absorption curves of various hemoglobin derivatives out to 10,000 Å.

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Chapter X

INFRARED PHOTOGRAPHY APPLIED TO BOTANY AND PALAEONTOLOGY

One of the most noticeable characteristics of the leaves of plants and grass is their green color. This is due to the presence of the pigment chlorophyll. Chlorophyll plays a very important part in the life of the plant. It facilitates the absorption of carbon dioxide from the air and enables the plant to form starch from it, by means of a mechanism which is not well understood. There are other pigments present in plants, the chief of them being carotene and xanthophyll. These generally accompany chlorophyll, and they are yellow in color. In some roots, flowers, and fruits these pigments may actually be present in complete absence of chlorophyll. When the green chlorophyll in leaves and fruit is destroyed by light or some other agency, the yellow pigments remain, and there is a rapid change of color from green to orange or yellow. It is not known whether these yellow pigments resemble chlorophyll in playing a direct part in assisting the assimilation of carbon dioxide.

When light falls on a leaf, part of it is reflected, part is absorbed by the materials of the leaf, and the rest is transmitted through it. A leaf has quite a complicated structure, and the problem of what happens to light when it passes through it is not nearly so simple as, say, in the case of a solution of a green dye in water. It has, however, been very much studied by biologists. The tissues cause the light entering it to be scattered. This is mainly due to reflection and refraction, and not to scattering by small particles such as occurs when light passes through a hazy atmosphere. The leaf pigments change the spectral quality of the light, an effect which is increased by the multiple reflections which the light undergoes inside the leaf.

A fair proportion of the radiation falling on a leaf is reflected at the surface. It ranges from about 2 to 15 per cent in the case

of the upper surface of green leaves and may be considerably higher in the case of white leaves or the white parts of variegated leaves. For green leaves this reflection is greatest in the middle of the green region of the spectrum between 5,400 and 5,600 Å. In this region it is of the order of 5 to 10 per cent for the darkest green leaves and may reach 40 per cent in the case of white foliage.⁵¹ With most leaves the reflection is at a minimum in the blue, rises in the green, and then drops to another minimum in the dark red at about 6,800 Å. As is shown later, chlorophyll exerts a very strong absorption at this point in the red. Beyond about 6,800 Å all leaves have a very high reflecting power which corresponds with a high transmission by chlorophyll. This was recognized as far back as 1890 in O. N. Rood's book on color.

In general, the under surfaces of leaves have a higher reflecting power than the upper surfaces. There are, naturally, variations from one kind of leaf to another, since different leaves vary in their physical structure and in the amount of pigment. There are also variations depending on the time of year and the conditions under which the plant grows and under which the reflection measurements are made. The main absorption of light by leaves is due to the pigment.

The extensive literature on the reflection, absorption, and transmission of different parts of the spectrum by leaves has been admirably surveyed by Popp and Brown.⁴⁰ By way of illustration of the spectral reflection characteristics of leaves, some curves are given in Figure 52. These were obtained by Richardson at the Kodak Research Laboratories. They show very clearly the characteristics mentioned and the variation according to the kind of tree.

Since the complex structure of the leaf presents difficulties in determining the absorption of the pigments, most of the measurements on them have been made on extracts dissolved in organic solvents. The curves obtained in this way are generally of the same form as those obtained on the leaves themselves, although there is usually some effect due to the solvent. For instance, in the case of alcohol and acetone extracts, the curves are shifted somewhat towards the shorter wavelengths, and the curves obtained on leaves themselves show much broader absorption bands than the solutions of the pigments.

Chlorophyll occurs in green plants in two forms known as the *a* and *b* varieties:

Chlorophyll *a* $C_{55}H_{72}N_4O_5Mg$

Chlorophyll *b* $C_{55}H_{70}N_4O_6Mg$

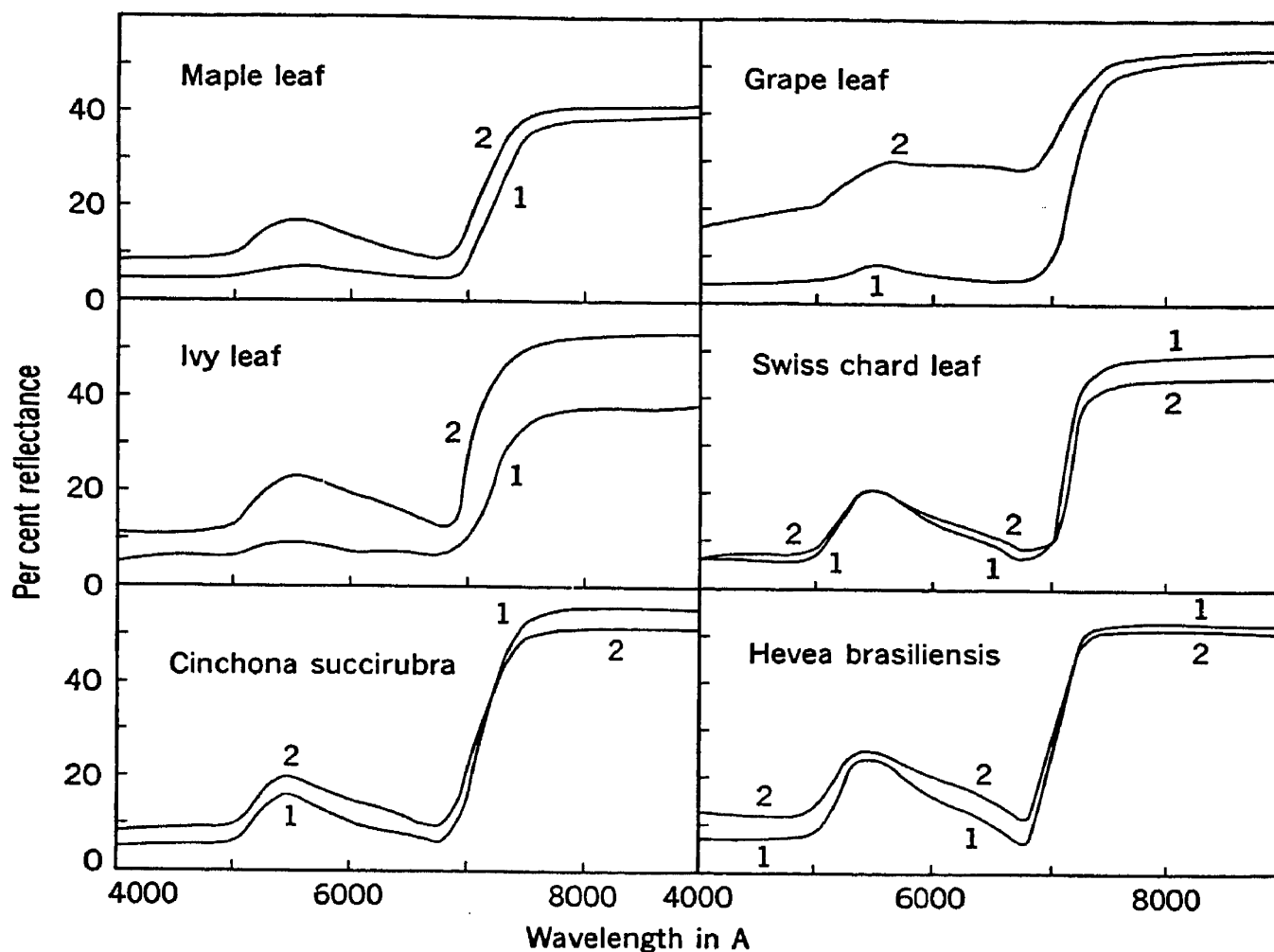


FIG. 52. Spectral reflection characteristics of leaves.

The curves marked 1 refer to the upper surfaces of the leaves, and those designated 2, to the under surfaces.

In most plants the ratio of the *a* to the *b* form is about 3:1. It was not until 1935 that the structure of the chlorophyll molecule was worked out as a result of the researches of Fischer. The difference between the *a* and *b* varieties consists in the replacement of a methyl group in the *a* form by a formyl group in the *b* form.

The two forms of chlorophyll show somewhat different absorption characteristics. Figure 53 shows the absorption spectra of

the two varieties in solution in ether, as obtained on the pure materials by Zscheile.^{59-61, 64} Other observers have obtained curves having similar characteristics,⁵¹ although the absorption coefficients vary. It may be seen that the curves show strong absorption maxima at 4,275 Å and 6,600 Å in the case of a chloro-

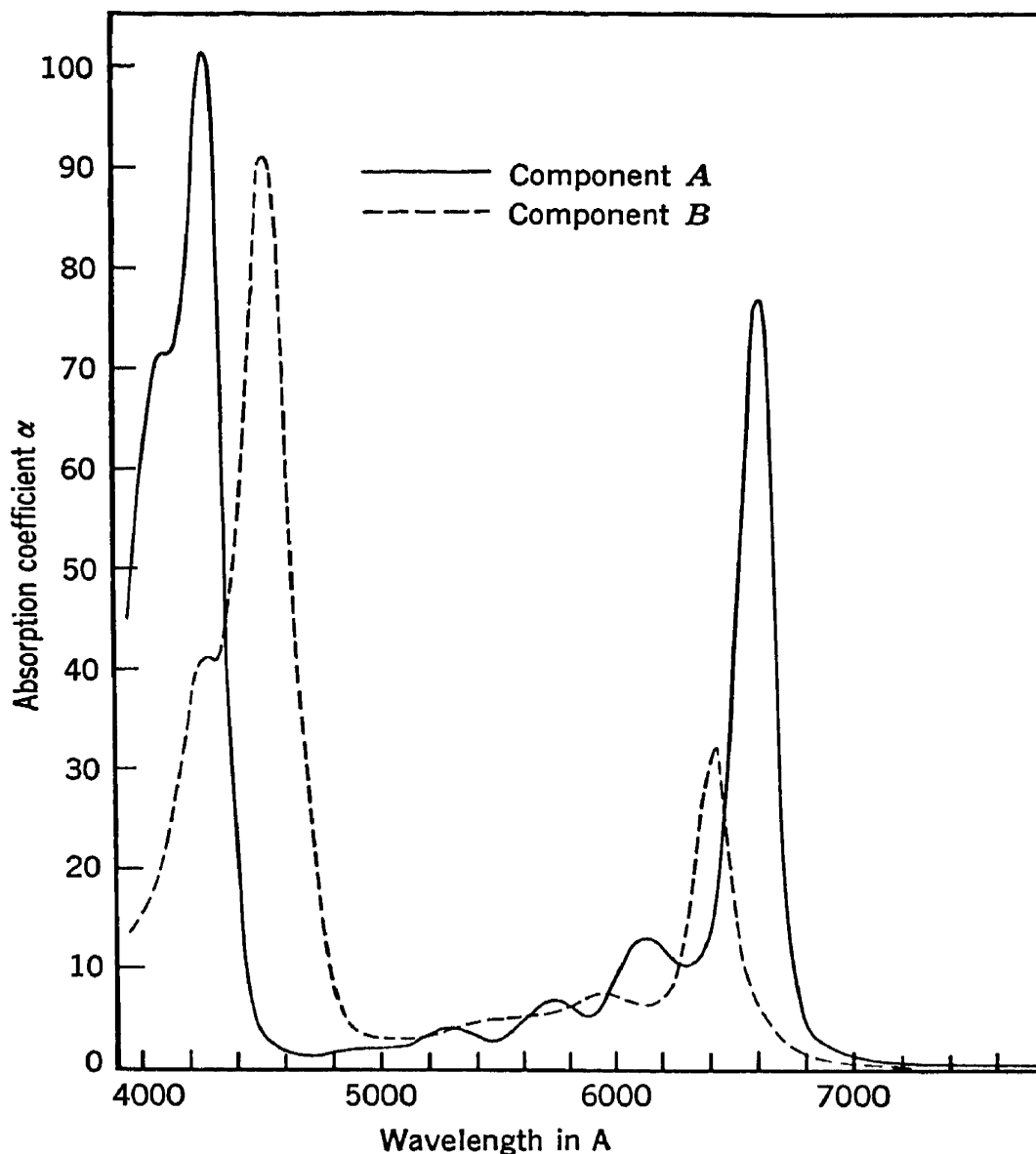


FIG. 53. Absorption spectra of chlorophylls *a* and *b* in ether. In the figure, component A refers to chlorophyll *a*, and component B to chlorophyll *b*.

The absorption coefficient α is defined as $\alpha = \frac{\log \frac{I_o}{I_x}}{cx}$, where I_o = intensity transmitted by solvent, I_x = intensity transmitted by solution, x = thickness of layer in centimeters, c = concentration of chlorophyll in grams per liter; the log is to the base 10, and α is expressed in liters per gram-centimeter.

(From F. P. Zscheile)

phyll, and at 4,525 Å and 6,425 Å in the case of the *b* component.

The data obtained by Zscheile apply to the visible spectrum. A number of measurements have been made in the infrared, notably by Coblentz and Stair,¹⁰ and van Gulik.²⁴ Chlorophyll is very transparent in the infrared. There is a slight absorption in the case of the *a* component between 8,000 and 9,000 Å according to van Gulik, but no strong absorption band occurs until the region beyond 34,000 Å. It appears that the infrared plays no part in the plant's photosynthetic reactions, a fact which is supported by the observations that there is very little absorption in the infrared. Only radiation which is absorbed can play a part in a photochemical reaction.

One of the most striking properties of chlorophyll is its fluorescence, which is shown both by the leaf and in solution. The fluorescence is of a strong red color. It was observed as long ago as 1833 by Brewster and was first studied by Stokes in 1852. Many observations have been made concerning the characteristics of this fluorescence, but there is a lack of agreement among different workers as to the actual position of the fluorescence bands in the spectrum. This appears to be due to the fact that chlorophyll is changed on exposure to light, and this results in some changes in the fluorescence bands, so that the results obtained at any time will depend on the exposure that the sample has had. According to Zscheile⁶²⁻⁶⁴ (Figure 54), the fluorescence spectrum of *a* chlorophyll in ether shows two maxima, at 6,685 Å and 7,230 Å, whereas the *b* form in the same solvent has three maxima, at 6,485 Å, 6,720 Å, and 7,050 Å. Albers and Knorr¹ considered that these results represented chlorophyll which had been changed by some exposure, and they stated that, at the beginning of exposure, the positions of the principal maxima are at 6,380 Å and 6,720 Å in the case of the *a* form, and at 6,370 Å and 6,570 Å in the *b* variety. Unfortunately, the method which they used for determining the maxima, although rapid, is not such as would be expected to give the highest precision. In the living leaf, chlorophyll is not nearly so susceptible to decomposition by light as it is in solution.

The fluorescence extends from the beginning of the visible red to the near infrared somewhat beyond 8,000 Å. In the leaf it

has a low intensity compared with that in solution. However, it can be observed very readily with the aid of suitable filters and an intense source of illumination such as the sun. An appropriate filter is the Wratten Dichroic filter no. 97. The fluores-

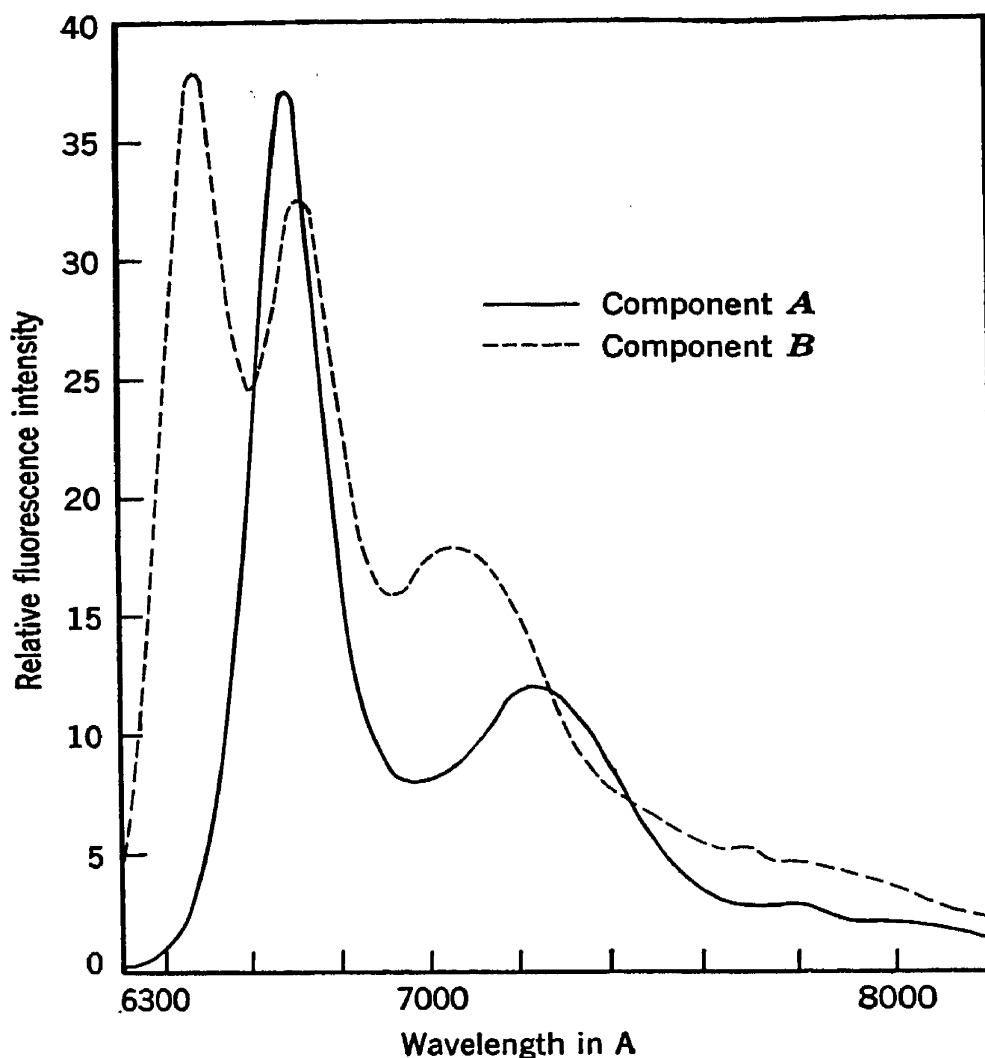


FIG. 54. Fluorescence spectra of chlorophylls *a* and *b* in ether. In the figure, component *A* refers to chlorophyll *a*, and component *B* to chlorophyll *b*.

(From F. P. Zscheile)

cence of chlorophyll has been used for distinguishing between camouflage and natural foliage in military operations.

Of the other plant pigments, the carotenes show a strong absorption in the blue, a fact which accounts for their yellow color. Both carotene and xanthophyll are very transparent in the infrared, the first strong absorption band appearing at about 30,000 Å (Stair and Coblentz⁵²). Mecke and Baldwin³² were

unable to find any natural plant pigments which had appreciable absorption at about 8,500 Å.

The optical properties of chlorophyll are of great interest to the photographer, because they determine the way in which green leaves are rendered in photographs made by light of different wavelengths. The properties of chief interest are the strong absorption band in the red, the high transparency in the infrared, and the fluorescence.

One of the noteworthy characteristics of infrared landscape photographs is the white appearance of the foliage of grass and deciduous trees as compared with its dark rendering in normal photographs. This has sometimes been ascribed to the high reflecting power of chlorophyll in the infrared. Although this may be partly true, the correct explanation is undoubtedly that, as a result of the extreme transparency of the chlorophyll in the infrared, the light reflected by the leaf tissues is no longer obscured by it. The tissues reflect the visible white light and the infrared very strongly. In the case of white light the chlorophyll absorbs much of it, so rendering the leaves as dark in the picture. In the infrared there is no such absorption, and the leaves are reproduced as bright.

Mecke and Baldwin³² and others have made infrared photographs of about a hundred leaves of different kinds, including some colored ones in the autumn. In all cases, provided the critical wavelength region of 7,000–7,500 Å was passed, the leaves lost their characteristic properties, except insofar as structural differences were concerned, and appeared equally bright in the infrared.

The explanation of the white appearance will be clear from a consideration of Figure 55, which is taken from the work of Willstätter and Stoll,⁵⁷ and which shows how light is reflected internally in a leaf. The light passes through the epidermis and the palisade cells, but is scattered diffusely and even reflected back towards its source in the spongy parenchyma, the interstices between which are filled with air. Mecke and Baldwin pointed out the similarity of behavior between the leaf and freshly fallen snow, the bright reflection of which is due to the presence of air between the small ice crystals. If snow is pressed

or tamped, it becomes darker and transparent. The same occurs in the case of a leaf. If the air is removed by the leaf being placed in a vacuum, and if it is then placed in water to fill the air spaces, no difference results which is visible to the eye, since the chlorophyll absorbs most of the light. In the infrared, how-

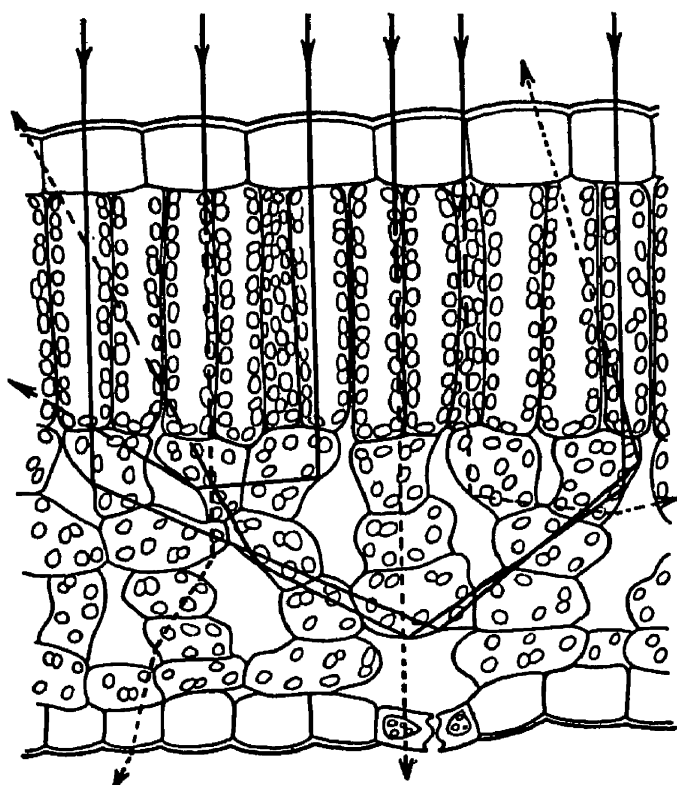


FIG. 55. Path of light rays in the structure of a leaf.

(From Willstätter-Stoll, Verlag Julius Springer, Berlin)

ever, to which chlorophyll is transparent, the bright reflection of the leaf is almost completely lost, and the leaf becomes relatively transparent. Obatan³⁶ realized that the high reflection in the infrared was not caused by the epidermis nor the cuticle. Dinger,¹⁵ who measured the reflection and transmission of leaves in the near infrared, found them to be high in the region from 8,000 to 13,000 Å, and found the water bands at 15,000 and 20,000 Å to be pronounced in the reflected as well as the transmitted radiation, indicating that a large portion of the reflected radiation is internally reflected.

Some pertinent observations have been made by Plotnikow and his assistants,³⁸ in their study of "scattering reflection." They showed clearly that chlorophyll in solution does not scatter infrared radiation, whereas plant tissues scatter it very strongly and even return much of it in the direction of the source.

The reflected light must be accompanied by the radiation in the near infrared owing to the fluorescence of the chlorophyll. In 1935, Dhéré and Raffy¹⁴ stated that the bright appearance of foliage in an infrared photograph is due primarily to the fluorescence of the chlorophyll. In a later article, however,¹³ it was concluded that this is probably only of importance in the spectral

region about 7,400 Å. Beyond this it is the high reflecting power of the tissues coupled with the extreme transparency of the chlorophyll which is significant. It is actually doubtful that the fluorescence plays a prominent part even in the shorter wavelengths. It is of low intensity indeed beyond about 7,500 Å.

That the bright appearance of leaves in an infrared photograph is not due to fluorescence at the longer wavelengths is evident from the fact that photographs made by radiation of wavelength longer than those in which chlorophyll fluoresces still show the leaves as very bright. This is clear from the series of photographs shown in Figure 56. The spectral regions by which these photographs were made were: (1) 4,500–6,900 Å, (2) 5,100–6,900 Å, (3) 7,400–8,500 Å, (4) 7,600–8,500 Å, (5) 8,500–9,700 Å, (6) 9,000–9,700 Å.

Mecke and Baldwin³² showed the unimportance of the fluorescence in another way. They illuminated leaves with blue light, which excites fluorescence in chlorophyll, and yet they were unable to obtain a photograph through an infrared filter, even when an exposure about 1,000 times normal was given.

Different types of foliage photograph differently in the infrared. In general, the leaves of deciduous trees show a high reflectivity, whereas those of conifers are reproduced much darker. This fact is used in photographic forest survey and is dealt with in more detail in Chapter XII, pp. 310–14. It is also of importance in camouflage detection in wartime, in particular in relation to the spectral reflectivity of paints. This subject is dealt with in Chapter XIII.

In general, the plant pigments other than chlorophyll seem to have optical properties resembling those of the aniline dyes, showing characteristic absorption in the visible spectrum, and practically complete transparency in the near infrared.⁵² As a result of this, flowers and fruit, such as oranges, tomatoes, and grapes, are reproduced in infrared photographs as if they were white. However, the natural vegetable pigments of the Indian marking nut (*Semecarpus anacardium*) and of the berries of the Chinese varnish tree (*Phytolacca clavigera*) are stated to be relatively opaque to the infrared. Infrared photographs, in fact, show very clearly the pigment cells in the pericarp of the nut when it is

cut in half. The black gills beneath the mushroom are opaque to the infrared and show their normal appearance in an infrared photograph (Mitchell³⁵).

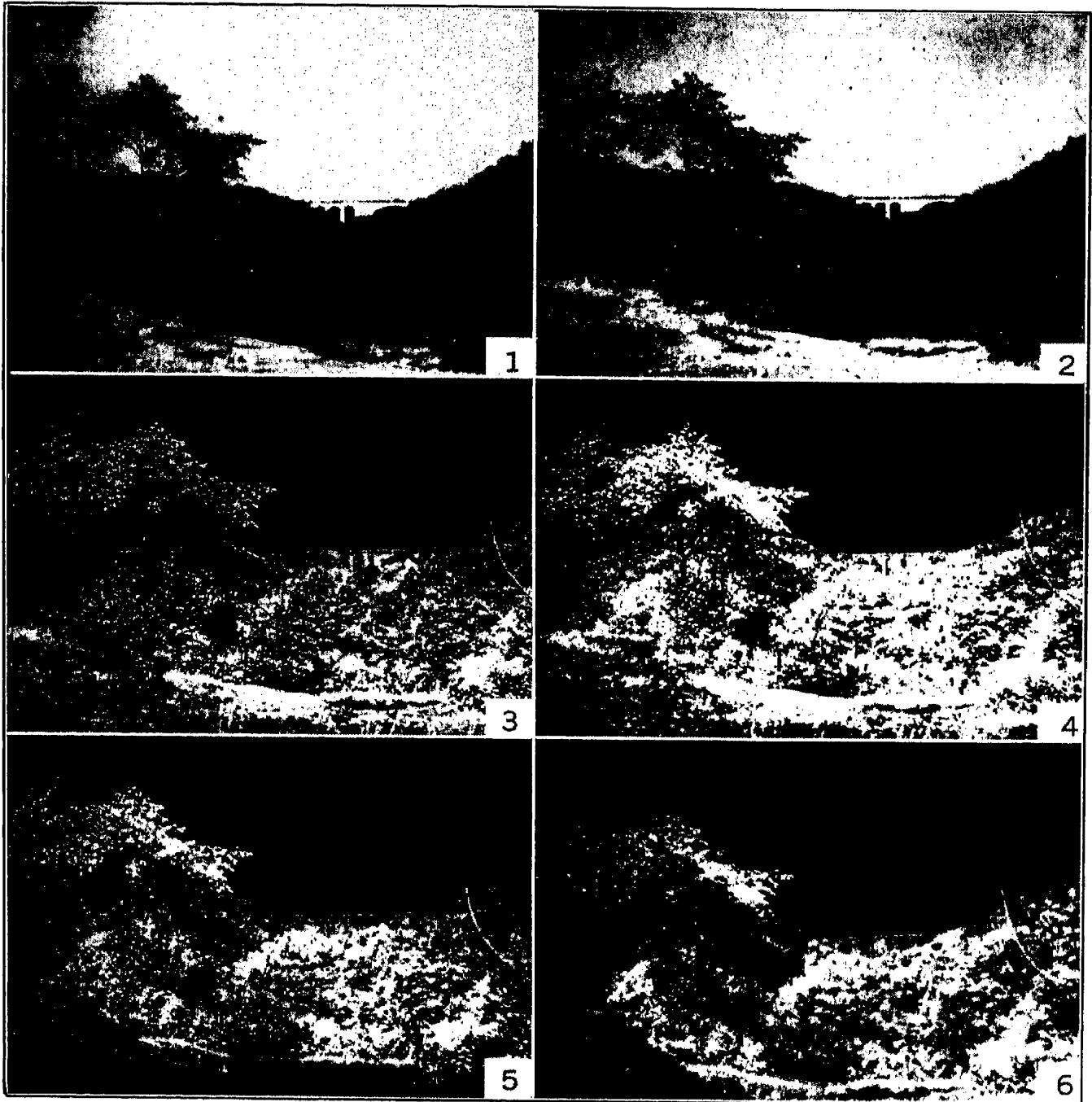


FIG. 56. Photographs of landscape by spectral regions of increasing wavelength.

Ives²⁸ has described the results of some experiments on the application of infrared photography to ecological survey from the ground. He recognized that healthy grasses and certain cacti are among the best reflectors of infrared, while mature and dry-

ing grasses and unhealthy cacti are poor reflectors; deciduous vegetation in general reflects well while evergreens are poor reflectors. Young needles are fair reflectors and appear lighter in an infrared print than mature needles. Ives feels that ten miles is the limit of the useful range in ecological work, except that it might be greater where only great changes in vegetation need be detected. Timberlines may be able to be detected at 50 miles on mountain ranges, but aspen patches in spruce-fir forests on the flanks of the same ranges have not been able to be detected. Infrared photography is said to be a valuable aid to ecological field work, but not a substitute for it. Each geographic area presents an individual problem.

Obatan ³⁶ measured the infrared reflectivity of leaves from the plains in comparison with those from the mountains. He claims the rather startling result that the mountain leaves reflect about twice as well as those of the plains. This is unexpected, when one considers that the chlorophyll is very transparent in the near infrared at both altitudes and that the reflectivity is determined mostly by the cellulosic structure.

PLANT PATHOLOGY

From the previous considerations it would follow that infrared photography should provide a useful means of studying and diagnosing plant diseases in which there is a change in the pigment or cellular material. For instance, if the chlorophyll or other constituents of the leaf cells were destroyed by parasites, or by drying or burning, it would be expected that the damaged areas would show up as light on a darker background in the negative, or dark on a lighter background in the print. This is actually found to be true.

Eggert ¹⁷ quotes examples which showed the effects of the dry summer in Germany in 1934. In fruit trees, the symptoms were a regular sharply defined zone extending from the edge of the leaf inwards. It was distinguishable from the burning due to spraying in that it was not distributed in the form of spots over the surface of the leaf, or confined to places where the spray fluid could collect in drops. The damaged parts of the leaves contained no living cells and no chlorophyll and showed up very clearly in infrared pictures, but not in photographs made by

visible light. Areas of defoliation in forests show up very clearly in infrared aerial photographs (see p. 312).

Babel⁵ made an extensive study of the applications of photography to plant pathology. In the case of gummosis of the cherry tree, the diseased branches could be distinguished visually only by the shape of the leaves, whereas in infrared photographs they showed up dark against a lighter background of healthy leaves. In the case of cucumbers affected by fungus, a normal photograph rendered the general appearance of the flecks more clearly than an infrared picture. On the other hand, the infrared showed dark-colored areas, not visible to the eye, which must have been the result of some cellular change caused by the fungus. It appears that, in general, normal photographs of leaves affected by fungoid growths show the affected areas with more contrast than those made by infrared, but if there is any change in the cell content the infrared enables superior records to be obtained. This is confirmed by photographs reproduced by Babel.

In the study of the potato virus disease, Bawden⁸ found infrared photography to be of much value. When ordinary panchromatic plates are used, there is difficulty in obtaining satisfactory photographs of the necrotic areas on the dark-green leaves in the case of the "streak" diseases. When infrared film is used, however, the necroses show up as black on a white background of the healthy part of the leaf. All necroses produced in the potato, regardless of the causative virus, show up in the same manner. In photographing the necroses produced in tobacco by the "X" virus, completely opposite results are obtained. The color contrast between the leaf and the necroses is such that they photograph well on panchromatic plates, but by infrared they are indistinguishable from healthy leaves.

This difference is explained on the basis that the potato necroses consist of dead cells which contain large amounts of breakdown products, rich in pectic products and possibly tannins, and these absorb the infrared very strongly. On the other hand, the "X" type tobacco necroses consist merely of dead empty cells, that is, of cell walls only, and these reflect infrared in the same degree as normal cells. By infrared photography, clear photographs can be obtained of incipient necroses barely visible to the eye, and Bawden expressed the opinion that, in ad-

dition to its use in recording disease symptoms, infrared photography may have a much wider application in the detection and differentiation of chemical changes actually occurring in the living plant.

In photographs of leaves made by visible light, it is generally very hard to distinguish between light brown and green. This is due to the fact that brown and leaf green are spectrally very impure colors, and it is difficult to select plates and filters which will separate them satisfactorily. This matter has been dealt with in an admirable manner by van Atta,⁴ in a study of the photography of living and dead leaves. Panchromatic materials alone were used. It was not possible to make very general rules, but on the whole it appeared that the greatest contrast was obtained using panchromatic materials and deep red filters, such as the Wratten no. 70 and the Zeiss RG5. The exposure through these filters is confined to the extreme visible red and appears to be due mainly to the light on the long-wavelength side of the strong chlorophyll absorption band at about 6,800 Å, to which chlorophyll is very transparent. In other words, the effect is that obtained in infrared photographs, but to a lesser degree.

Babel⁵ has pointed out that infrared photography should also be useful for showing the presence of small insects, particularly when it is realized that many are difficult to distinguish visibly owing to mimicry.

BOTANICAL PHOTOMICROGRAPHY

Much success has been achieved in infrared photomicrography in the botanical field, and this is treated in some detail in the section of this book dealing with photomicrography (Chapter XI). Of particular interest are the publications of Prát and his coworkers⁴¹⁻⁴⁶ in Prague. The method depends for its success largely on the fact that the cell walls and the chloroplasts are more transparent to infrared than to visible light and thus make possible the rendering of detail in the cells themselves.

TRANSPARENCY OF WOOD TO INFRARED

It is well known in infrared photographic practice that wooden draw slides in the plateholders should be avoided; otherwise there is a serious risk of fogging the plate by infrared transmitted by

the wood. In fact, infrared photographs have actually been made in the camera without the wooden draw slide being removed, and shadow photographs have been made after the manner of radiographs, without the slide being withdrawn. Danckwortt,¹¹ Kaku,²⁹ Bäckström and Johansson,^{6, 7} Tonzig and Viterbi^{53, 54} have reported a high degree of transparency of wood, and the matter has been studied in detail by Prát and his assistants.^{43, 46} Fortunately wood is not used in modern draw slides.

To compare the transparency of different kinds of wood in the infrared, Prát⁴³ made wooden wedges, tapering from a sharp edge at one end to 8–9 mm thick at 9 cm from the edge. Longitudinal tangential sections were employed, and the wedges were used directly as photometric wedges in contact with the infrared plate (Agfa 810 Hart). The source of radiation was a 150-watt Philips Argenta lamp with an opal glass bulb operated at 120 volts, 1 ampere, at a distance of 2 m from the wedge. The exposure was 6 seconds. The thickness of wood under which a perceptible density was obtained on the plate was as shown in Table XXII.

TABLE XXII

THICKNESS OF WOOD PERMEABLE TO INFRARED

Wood	Mm	Wood	Mm
<i>Larix europæa</i>	5–7	<i>Carpinus betulus</i>	2–3
<i>Abies alba</i>	6–7	<i>Fagus silvatica</i>	3
<i>Picea excelsa</i>	6	<i>Ulmus</i> sp.....	(3), 1
<i>Alnus glutinosa</i>	5–6	<i>Quercus</i> sp.....	2
<i>Tilia</i> sp.....	4–6	<i>Prunus domestica</i>	1–2
<i>Pinus</i> sp.....	3–4	<i>Prunus avium</i>	1–1.5
<i>Populus</i> sp.....	4	<i>Juglans regia</i>	0.5
<i>Acer</i> sp.....	4		

With the same conditions of illumination, none or only feeble penetration was recorded when fast orthochromatic plates were used instead of those sensitive to the infrared. Samples of wood which showed marked variability in infrared transmission were all equally transparent to X rays. Some of Prát's photographs are reproduced in Figure 57.

Rawling⁴⁷ also examined the transparency of wood to the infrared in connection with the study of draw slides. Using

pieces of wood 3 mm thick and Ilford infrared plates, he obtained the results shown in Table XXIII which are quoted from his book.

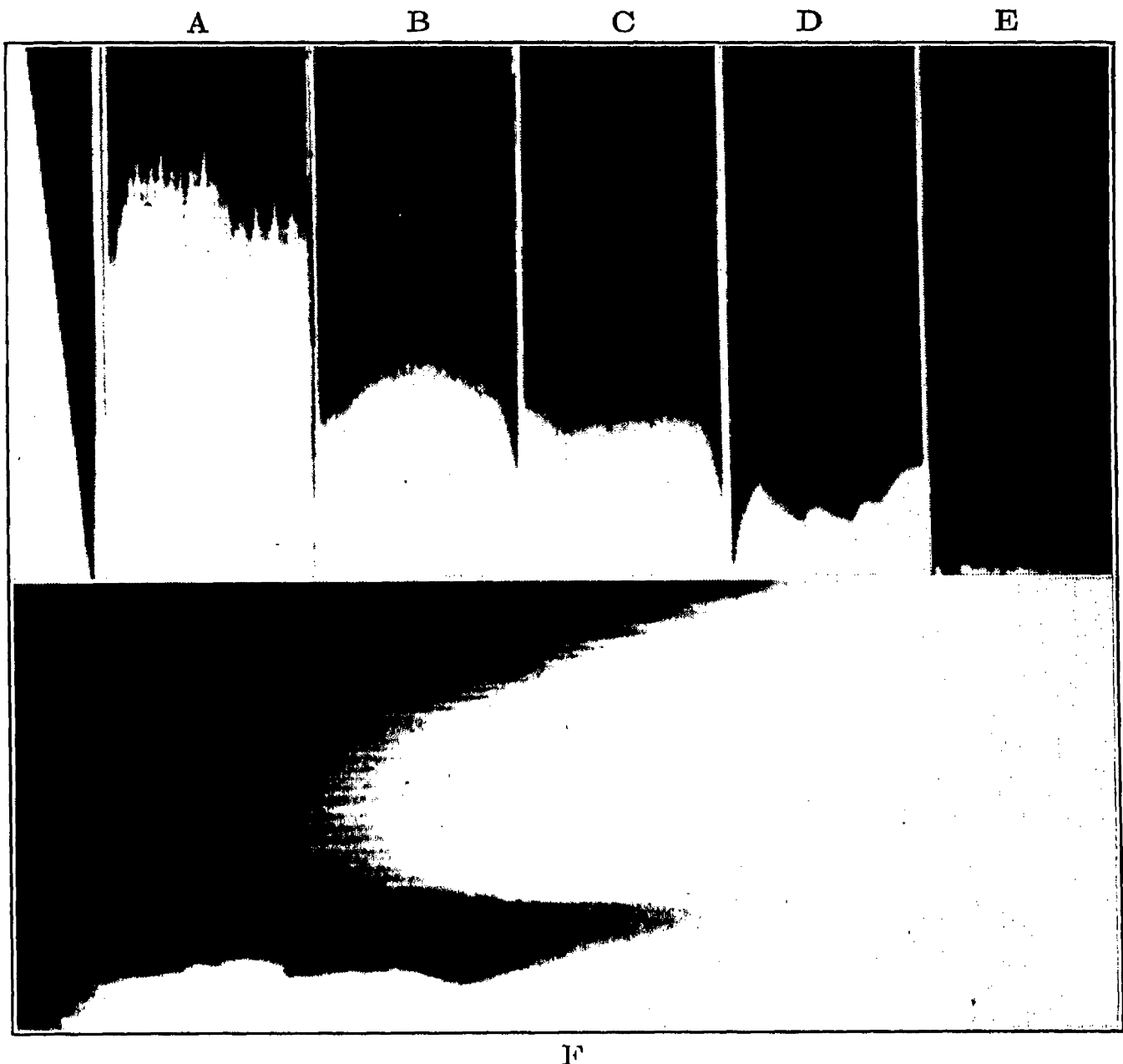


FIG. 57. Infrared transmission of wood.

The samples of wood had the shape of the dark wedge shown at the left-hand side of the upper series of photographs. A, *Larix europaea*; B, *Tilia*; C, *Acer*; D, *Prunus*; E, *Juglans regia*; F, *Larix europaea*.

(Courtesy S. Prát)

In 1943, Delay and Lecomte¹² published quantitative data on the infrared transmission of wood which confirmed the findings of earlier workers.

TABLE XXIII

TRANSMISSION OF INFRARED THROUGH WOOD

<i>Wood</i>	<i>Exposure Given</i>	<i>Photographic Effect</i>	<i>Behavior to Infrared</i>
Siberian pine	1 sec at 6 ft from 500-watt gas- filled lamp	Considerable	Transmit freely
Yellow deal		Considerable	
Sycamore		Some	
Boxwood		Some	
Beech		Slight	
Yellow pine	5 sec at 6 ft	Considerable	Some transmission
Tasmanian oak		Considerable	
Indian teak	400 sec at 6 ft	Considerable	
Honduras mahogany		Some	Almost opaque
Jarrah (Australia)		Some	
English oak		Slight	
Australian walnut	2,000 sec at 2 ft	Slight	
African walnut		Slight	
American walnut		None	Opaque
Indian silver-grey wood		None	
Iroko teak		None	
Ebony		None	

PALAEOBOTANY

In the lignite mines of the Geisel valley, near Merseburg, Germany, Weigelt discovered in the Middle Eocene strata a whole series of well-preserved fossils, including those of plants. Infrared photographs of some of these showed that they reproduced exactly like similar photographs made of living leaves.¹⁷⁻²⁰ They appeared light in the picture, whereas when photographed by visible light they were rendered dark.

In 1935 Walton⁵⁶ published some photographs which showed that infrared photography may be of considerable value in coal petrology. Transfer preparations of fossil plants, particularly those of the Carboniferous age, vary in their transparency to visible light, some of them being so opaque as to render photomicrography difficult. Some of them are transparent to the infrared, however, and infrared photomicrographs show detail otherwise invisible. Similar results have been found by others, and Walker and Slater⁵⁵ have stated that they have made many hundreds of similar photographs which showed the usefulness of the method. They make the following observations: Coal sec-

tions consist of heterogeneous mixtures of substances of the following colors: white (empty spaces); brilliant yellow (spores and cuticles); and a continuous series of shades from pale red

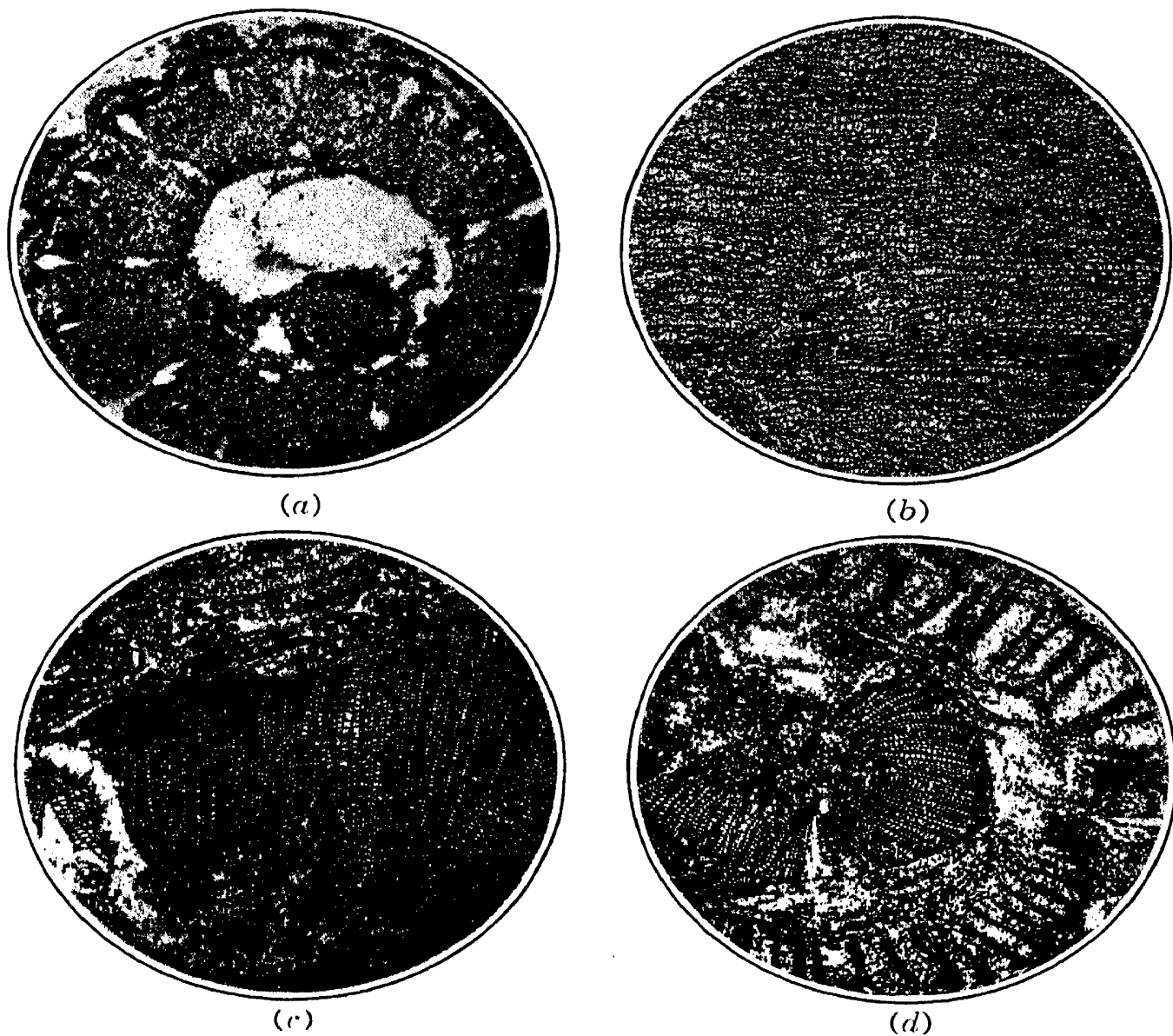


FIG. 58. Infrared photomicrographs of coal sections.

(a) Transverse section *Lepidodendron Vascular*.

(b) *Cordaites* transverse section wood.

(c) *Calamites*.

(d) *Lyginopteris oldhamia*.

(Courtesy F. Martin-Duncan)

through deep red to black (vitrain, fusain, and so on). When panchromatic films are used to photograph such sections, the color contrast is increased, while in infrared photography this is rendered much more satisfactorily, resulting in more realistic

pictures. In certain cases, however, panchromatic films are to be preferred: for example, in photographs of the cell structure in vitrain, where there may be no yellows and whites, and where contrast may be desired.

In 1941 Martin-Duncan showed a group of infrared photomicrographs of coal sections at the Exhibition of the Royal Photographic Society. Some of them are reproduced in Figure 58. They clearly show fine detail of structure in relatively thick dense dark-brown sections of fossil stems of plants of the Carboniferous period from the coal strata of Yorkshire and Scotland.

PALAEONTOLOGY

Infrared photography was applied with a certain measure of success to the investigation of the fossils found by Weigelt in the lignite of the Geisel valley. Photographs of fossil frogs from this region have been published by Eggert,^{17, 18} Fröhlich and Luft,¹⁹ in which details were reproduced by infrared which were invisible, or were visible only with difficulty in pictures made by red light. Eggert suggests that the success of the infrared method is due to the ability to penetrate the overlying lignite layer, and this would appear to be in accord with the observations which have been made on thin coal sections by other investigators.

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Chapter XI

INFRARED PHOTOMICROGRAPHY

The microscope stands in the forefront among the instruments which have proved of value as weapons of scientific and technical investigation. Although it is a very old instrument, before the invention of photography the only way in which a permanent record could be made of what the observer saw in his microscope was by making a drawing. This procedure, while giving very elegant results, could not be considered to give an infallible record of all the details observed, nor of their respective tone values. It was not until photography was invented that a true record of the image in the microscope could be made in permanent form, and it is not surprising that practically the first use of photography in the scientific field was to record this image. In 1802 Wedgwood and Davy made photomicrographs on white leather soaked in silver nitrate, using the so-called solar microscope, but they could not fix them. The first permanent photomicrographs were made in 1837 by Reade, who had discovered fixation by hypo.

By skilful understanding of the use of the microscope, and a knowledge of the properties of photographic plates and films, photomicrographers are able to obtain results showing fine details with the utmost clarity. They understand fully the conditions necessary to obtain these results, and by the use of light filters they can control the contrasts of differently colored parts of their subjects to any desired extent.

In 1926 in a discourse at the Franklin Institute in Philadelphia on the color sensitivity of photographic materials Mees¹⁹ made the following prophecy concerning photomicrography: "Until quite recently, the microscope has remained a visual instrument, the photomicrographic methods being employed only to depict what had already been seen. It seems likely that before long the microscope in its turn will become a photographic instrument, the

visual observation being used only to guide the instrument to the photography of the unseen." Mees had in mind specifically the use of the invisible ultraviolet in photomicrography. His remarks might have applied also to the invisible infrared at the other end of the spectrum, had infrared-sensitive photographic plates and films been available for use with the ease of normal photographic materials. The use of infrared in photomicrography, however, would not depend on an increase in resolving power such as is obtained by the ultraviolet, for this is indeed lower in the infrared, but on the greater transparency of many materials to infrared radiations. There is no advantage in increased resolution if the object photographed is opaque, and resolving power may well be sacrificed if a means is available for penetrating the opaque materials.

Many years earlier Mees himself had studied the dyes commonly used for staining biological preparations for microscopic investigation, and had established the basic rules according to which stained sections should be photographed in order to obtain the best rendering of detail and of contrast with orthochromatic and panchromatic plates and films. The principles which he laid down were the following:

In order to obtain the maximum rendering of detail, photograph the subject in light which is transmitted by it or by the stain.

In order to obtain the maximum contrast, photograph the subject by light which is absorbed by the stain.

One would expect these principles to apply to photomicrography by infrared, just as much as they do to photography by visible light. Most biological stains which are used for visual microscopy, however, are very transparent to the infrared. In order, therefore, to obtain satisfactory rendering of contrast in the infrared, it is necessary to select those stains which absorb the infrared in the region of the spectrum to which the plate or film responds. If satisfactory rendering of detail is to be obtained, the subject must be transparent to the infrared in this region. It is in this sense that infrared photomicrography has proved particularly useful, because many materials which are opaque to visible light are transparent to the infrared.

PRACTICAL INFRARED PHOTOMICROGRAPHY

Within the confines of this book it is impossible to deal with the technique of making photomicrographs. It is assumed that the reader is acquainted with this, or that there is available to him one or more of the books which have been published on the subject.^{11, 29}

The first attempts at photomicrography with long-wavelength radiation appear to have been made by Köhler³ in 1912-13. Since at that time plates sensitive to the infrared were not available commercially, he used Wratten Process Panchromatic Plates, confining his exposures to wavelengths beyond 6,400 Å by means of filters. The sensitivity of the plates did not extend beyond about 7,100 Å and so the photographs were actually made by deep red light and not by infrared (see Berger³).

In 1927-29, Calzavara, Bertrand and coworkers^{4, 5, 8, 9} published a series of works in which the problems of infrared photomicrography were discussed fully. They described clearly the conditions necessary for obtaining good contrast and detail, and the photomicrographic technique which they employed was based on the following considerations:

I. The particular characteristics of the infrared between 7,600 and 10,000 Å. In this region the radiation is less refrangible and can penetrate media which are impermeable to visible light.

II. Sensitization of plates in the infrared by cyanine dyes which confer sensitivity in a region widely separated from the region of natural sensitivity of the plate.

III. Use of photographic sensitizers as histological stains, in such a way that the absorption curve of a stain coincides exactly with the sensitization band of the plate.

IV. Use of a filter to eliminate the radiations which do not have the wavelengths to which the plate is sensitized, in such a manner that only those radiations are employed which correspond both to the absorption of the stain and the sensitized region.

In the practice of these authors, Kryptocyanine was used both as the stain and as the sensitizer for the photographic plate. An apochromatic immersion objective having a numerical aperture of 1.30 was employed, in conjunction with an aplanatic condenser

of aperture 1.4, and a Zeiss Homal 4 ocular. As light source, an incandescent filament lamp of 600 candle-power was used, with a relatively small diaphragm to utilize only those rays close to the optical axis. Wratten filters nos. 88, 88A, and 87 were employed. Focusing was effected visually, and then, in order to ensure focus in the infrared, the fine adjustment was changed by an amount which had been determined previously by making a series of photographs at various settings (see p. 280).

The book of Bertrand and Justin-Besançon⁴ contains a large number of excellent reproductions of photomicrographs obtained in the manner described, and the morphological and histophysiological implications are discussed. They bear specifically on renal cytology. In other publications, they applied their practice to other cytological studies, particularly to cancer, and to the central nervous system in normal and pathological conditions.

It might seem that results similar to those obtained by these investigators could be produced by using panchromatic plates and filters with narrow transmission bands. They point out, however, that their technique would be expected to give superior results, because infrared sensitizers are available which give very sharp isolated sensitizing bands and sharply absorbing bands of the same wavelength when used as stains. In the case of normal stains, panchromatic plates, and filters, it was difficult to isolate a photographic spectral region which corresponded closely with the desirable part of the stain characteristic. With the present knowledge of sensitizing dyes and filters, it is probable that this could be achieved more satisfactorily than at the time when Calzavara and Bertrand made their studies.

Photomicrography by infrared, as usually carried out at the present time, scarcely differs in principle from photomicrography by visible light. The source of radiation is selected so as to have ample energy in the region to which the plates and films respond, filters being used to confine the exposure to the desired spectral region. Infrared-absorbing stains are used or not, according to the contrast and rendering of detail desired. There are a number of factors to which special attention must be paid in working in the infrared region. The most important of these are due to the fact that existing microscope lenses are made for use with visible

light and that the infrared image is invisible. Focusing, therefore, presents a special and important problem.

From the chromatic aberration curves for apochromatic and achromatic objectives, it follows that the former are much to be preferred for infrared photomicrography (see Chapter XVI). If apochromats are used, it is probable that no correction of the focus will be needed over that obtained visually with a deep-red filter, such as the Wratten no. 29, or even a tricolor red filter, such as the no. 25. Most infrared photomicrography, however, is done at low powers, where only achromatic objectives are available, and the marked chromatic aberration of achromats may require a considerable readjustment of the focus for the infrared. These lenses vary very much among themselves, and so the correction necessary will depend on the particular objective in use. In addition, it is to be expected that appreciable degradation of definition would occur if a wide band of wavelengths in the infrared were used.

A number of methods are employed in practice for obtaining good focus:

1. Focusing visually in red light.
2. Photographic calibration of the fine adjustment and application of a correction.
3. The method of correction of Naumann.

1. In the first method, the image is focused visually on the ground glass with a red filter in position; then the infrared-transmitting filter is brought into position, and the exposure is made. If the photograph is made by infrared radiation lying just outside the visible spectrum, focusing through the red filter will suffice with apochromats and perhaps with certain achromats. If the photographic plate has a narrow band of sensitivity about 8,000 Å, as is the case with the common infrared films and plates, it is often sufficient to focus and photograph through the same filter, such as the Wratten no. 25 or 29, the Ilford Tri-colour Red or Spectrum Red, and the Agfa no. 81 or 82.

If it is desired to confine the infrared exposure to longer wavelengths, it is necessary to use a filter which has its "cut" at longer wavelengths and which transmits little or no visible light. In such a case, focusing is effected with one of the filters named,

and for exposure this is replaced by one of the following: Wratten nos. 70, 89, 89A, 88, 88A, or 87; Ilford Infra-red; Agfa nos. 83, 84, 85, 87, 88, or 89. Kraft¹⁷ has described a combination filter consisting of a Schott red glass RG5, 2 mm thick, and a Schott blue glass BG3, 2 mm thick. For photographing in the region 8,000–10,000 Å, visual focusing is carried out through the red filter alone, the blue filter being added to the red for the exposure. The combination of the two filters transmits only beyond about 7,500 Å, that is, beyond the end of the visible red. Naturally, the photographic film must be selected to have as much sensitivity as possible in the region of the infrared transmitted by the filter. When one is photographing by the longer-wavelength infrared, and particularly when achromats are used, it may be necessary to use the second method of focusing.

2. In the second method, a test object is placed on the microscope stage and focused visually by green light in the normal way, and the setting of the fine adjustment is observed. The infrared filter is then placed in position, and a series of exposures is made on infrared plates with different settings of the fine adjustment. Examination of the negatives will permit the selection of the one showing best focus. A note is then made of the difference between the settings of the fine adjustment for best visual and best photographic focus. In making photographs at any later time the subject is focused visually, and this correction is applied before the exposure is made. A sharp negative should result.

3. A modification of the second method is due to Naumann.²⁰ From an examination of the curve of residual chromatic aberration of a number of achromatic and apochromatic objectives (corrected for 4,861 and 6,563 Å), he concluded that the difference in focus between wavelengths 5,400 Å (corresponding to the minimum in the curve) and 6,800 Å is about equal to half the difference in focus between this wavelength and the infrared at 8,200 Å. If it is found by trial that this relation applies to the objectives used, the following procedure can then be used in focusing for the infrared: the object is first focused visually in green light, with a filter having its maximum transmission at about 5,400 Å (Wratten filters nos. 58, 58A, or 61; Ilford Tricolour Green; Agfa no. 70). It then is focused visually in red

light, with a filter somewhat darker than the normal tricolor red filters (Wratten no. 29; Ilford Spectrum Red; Agfa no. 42 or 82). The difference between the settings of the fine adjustment is noted, and the fine-adjustment screw then is turned still further, in the same direction as for the red filter, to an extent equal to twice this difference. The infrared image should then be in focus, but the factor will vary with the achromat.

TABLE XXIV

<i>Focus</i>	<i>Filter</i>	<i>Centroid Wavelength</i>	<i>Deviation in Focus from That of He Line (5,876 Å)</i>
1st focus	Wratten 90 plus CuSO ₄	5,800 Å	0.000034
2d focus	Wratten 29	6,350 Å	-0.000290
2d focus (alternative)	Wratten 70	6,900 Å	-0.000798
3d focus	Wratten 87 and infrared plate	8,200 Å	-0.002347

Multiply all deviations by 10^6 for convenience.

	<i>Difference</i>	<i>Ratio:</i>	<i>Green to Red Focus Red to Infrared Focus</i>
1. Δ (90-29)	324		
2. Δ (29-infrared)	2,057		6.3
3. Δ (90-70)	832		
4. Δ (70-infrared)	1,549		1.86

R. P. Loveland and M. Herzberger* have revised the Naumann correction basing the values on the more recent focal deviations as calculated by Herzberger (see Chapter XVI). For the Micro-Tessars of Bausch and Lomb and Zeiss they apply the following procedure; it probably applies to the Micro-Summars:

For the green filter of high efficiency having a narrow transmission band there is used a combination of the Wratten no. 90 filter with a liquid filter of 10 mm of copper sulphate ($\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$, in 5 per cent solution). If the copper sulphate is added to the cooling cell and the thickness is different, the appropriate change in concentration must naturally be made. The data for the method are given in Table XXIV. To apply the method, the microscope is first focused visually through the

* Private communication.

green filter Wratten no. 90 plus CuSO_4 , and the focus position on the adjustment is marked as zero. The red filter, preferably the Wratten no. 70, is then substituted, and the microscope is refocused (after the focus of the lupe has been checked for green and red). The shift of the objective is noted, and it is moved further by the factor given under "Ratio." If there is any play (backlash) in the focusing mechanics, all focusing must be done in the direction toward the green-to-red shift.

The characteristics of plates, films, and filters for infrared photography are described in various chapters in this book, and, in order to avoid repetition here, the reader is advised to consult them.

In the selection of a source of infrared radiation for photomicrography, the same principles apply as for normal infrared photography (see Chapters II and VII). In practice, it happens that the sources commonly used for photomicrography by visible light are also suited for work in the infrared. The common arcs, tungsten-filament or ribbon lamps, and the Pointolite are perfectly satisfactory.

The exposure for infrared photomicrography is determined by making a series of exposures in the manner normally employed in photography by visible light. This can be done by using a special device, such as the Zeiss multiplier, or simply by making a stepped series of exposures on one film, pushing in the draw slide for a short distance at known intervals of time.

There is no essential difference in the development of infrared film and of those used for work in the visible. The nature of the developer and time of development are so selected as to give the desired contrast. Formulas for developers and particulars of development times are given in Appendix III.

An important point which has already been discussed, but which should be emphasized again here, concerns the nature of the material of the film holders used in infrared photography. Most of the holders commonly used in microscope cameras are constructed of wood and have wooden or hard-rubber draw slides. Wood in thin layers and certain types of hard rubber are very transparent to infrared radiation. Infrared film kept in them will be badly fogged if they are exposed to light, even if they are closed. Metal holders are perfectly safe, as are some of the

modern types of hard-rubber draw slide. Certain manufacturers actually select their hard rubber to be opaque to infrared. If nothing is known of the origin and nature of the material of a slide, it is as well to test its safety in the manner described on p. 14.

APPLICATIONS OF INFRARED PHOTOMICROGRAPHY

BIOLOGICAL APPLICATIONS

Most of the work in this sphere has been done with biological specimens, particularly in the fields of entomology, cytology, histology, embryology, and botany. In general, infrared photomicrographs of deeply pigmented tissues and the thicker microscopic sections and specimens show details of internal structure which are not visible in ordinary photomicrographs.

Of particular interest in this connection are the photographs of insects, of which a large number have been published by various investigators.^{17, 27} The structure of many insects contains dark chitin which renders the study by visible light very difficult. In such work it is customary to bleach the specimen, for example, by means of potash, a treatment which requires both time and care and may result in damage to the preparation. Photomicrographs made by infrared of the unbleached subject very often show just as much detail as those made on the bleached subject by visible light. In some cases, the specimen is so thick that infrared does not show all the desired detail, and it is necessary to resort to the use of grenz radiography. This, however, involves the use of expensive electrical radiographic equipment, and the infrared method is obviously to be preferred if it gives the desired results.

Even in the case of fossil graptolites from the Lower Silurian (*Diplograptus gracilis* F. Roem), which consists of chitin that has become carbonized in the course of time, Kraft¹⁷ was able to make photomicrographs by infrared which rendered the specimens quite transparent and showed up the fine structural detail.

In addition to the study of graptolites, Kraft¹⁷ found that infrared photomicrography could be used for the investigation of the structure of other carbonized organic remains from fossil sediments, such as prints from the coal beds, scales of fossil fishes,

the hairs from fossil animals, including mammoth hairs from the Siberian ice. Pax²² successfully applied infrared photomicrography to the study of coral skeletons. Some of these are colored dark brown or deep black and are quite opaque to visible light, whereas the infrared penetrates them readily.

Many studies have been made of the application of infrared photomicrography in the field of cytology. The first investigations were made by Calzavara and Bertrand and described in works to which reference already has been made. They claimed that the use of the infrared enabled them to study the fine structure of the plasma, nucleus, and so on, in a manner that was not possible visually. Preissecker²⁵ came to a similar conclusion and expressed the opinion that photomicrographs in the infrared are of very special importance for histology. This is borne out by the illustrations accompanying his paper. He pointed out that, in sections strongly colored red, density differences in the same color region showed up clearly in infrared photomicrographs, whereas they could not be shown up by ordinary methods.

In neurohistological studies, Blair and Davies⁷ showed that in the case of silver preparations of nerve fibers, infrared photomicrographs were far superior to those obtainable by the use of panchromatic plates and filters. Infrared did not help in the case of osmic acid preparations, but the structure of the cytoplasm of ganglion cells darkly stained with silver nitrate was well revealed.

Gigon and his collaborators,^{14, 15} who made a very extensive study of the transmission of red and infrared radiation by the tissues of different animal organs, published many results which are of value in showing the success to be expected in the use of the infrared. In particular, they investigated the blood in various conditions. One of Gigon's students, Binkin,⁶ used infrared to examine the influence of injections of insulin-phloridzin and thyroxin on the tissues. He stated that the infrared pictures were sharper than those obtained by visible light. From numerous photographs of liver sections he concluded that the thorotrast was the least transparent in the infrared; then followed blood with a relatively low transmission, then the liver cell walls, and finally glycogen, which was the most transparent. He expressed the definite opinion that infrared photomicrography would prove

a useful tool for the investigation of pathological-anatomical processes in the tissues which cannot be clearly observed (see also Chapter IX).

Infrared photomicrography is of interest in the study of routine microscope sections of tissues stained with any of the red or brown stains, or in tissue where the natural pigment is reddish or brownish in color. Massopust¹⁸ has described a number of cases in which photographs were made by reflected and transmitted light, and with or without a filter. Infrared photographs of a section of the human kidney, stained with hematoxylin-eosin, as compared with photographs made by green light, showed good color definition and separation of detail. There was improvement in the rendering of detail in a sclerosed glomerulus, while the nuclei in other glomeruli and in the tubular structures showed increased contrast. More transparency of the muscle tissue was obtained, and even greater transparency of the injected material within the blood vessels. There was also excellent differentiation between the deep red color of the blood vessels and the brownish color of the muscle tissue. These infrared photomicrographs were made without a filter, and therefore part of the exposure was due to blue and violet light.

Massopust¹⁸ also showed photomicrographs of a section of the human fetal eye. The large artery was packed with water cinabar mixture, vermilion in color, while the veins contained black India ink. In photographs by transmitted green light it was impossible to differentiate between the artery and the veins. By infrared without a filter, and by reflected light, the vermilion of the artery was recorded with an unusual amount of brightness as compared with the black color of the veins. In order to cut down this contrast, the infrared plate was first exposed to transmitted and then to reflected radiation. Somewhat better definition of the structure was obtained without entirely destroying the contrast between the artery and the veins. It is thus possible to exercise control over density and contrast by this method of injection and photography.

In a study of the architecture of the blood vascular networks in the mucous lining of the nasal passages, Swindle³¹ has found this procedure to be of considerable advantage. One interesting device which he employed, and which gave a semblance of three-

dimensional effect, consisted in photographing by reflected and by transmitted infrared on separate plates, superimposing the two negatives, rephotographing the combined negatives to give one negative, and printing from this.

Nicholas²¹ found that infrared photography is useful in the study of embryology. For instance, he found that it is particularly applicable to the earlier stages in the case of the rat. As compared with photographs obtained by green light, infrared photographs showed sharper outlines and better depth and definition. This was for embryos 1.25 mm long and 0.3 mm in diameter. With subjects 1.8 mm long and 0.5 mm in diameter, the green-sensitive plate gave better results than the infrared. Embryos 10 mm, 15 mm, and 25–30 mm long could be photographed for internal structure only by using the infrared. The results were better than with radiographs, since they showed structures in silhouette to a much greater depth and in better perspective. Massopust¹⁸ also published a series of photographs of embryos in which substantially the same advantages of the use of the infrared were evident. His sections were stained with carmine, which is transparent to the infrared. Cross sections of bone stained with silver nitrate showed improved definition in infrared photographs.

Infrared photomicrography has been applied with success to the study of cellular structure of botanical specimens, particularly by Prát.^{23, 24} The cell walls, especially when colored, are often more transparent to infrared than to ordinary light, so that details in the cells not normally visible may appear very distinctly in infrared photographs. Prát also reports good results from objects encrusted with calcium carbonate, such as corals (Pax²²), and calcareous algae, Coralline and Melobesia (Prát and Hrubý²⁴). He points out that the most striking difference between photographs by visible light and those by the infrared is in those of cells with chloroplasts. Since the pigments absorb most of the effective light, the chloroplasts appear dark and without structure in normal photographs. On the other hand, they are transparent to infrared, and therefore appear to be transparent or to possess a definite structure in the infrared photographs. In staining fixed sections with Heidenhain's iron alum-hematoxylin, the chromosomes, centrosomes, and pyrenoids as-

sume a deep black color, are visually quite opaque, and reproduce without detail in normal photographs. When photographed by infrared, however, they are penetrated and reveal a definite structure. When stained with the Heidenhain stain the cytoplasm often appears grey, but it is rendered as almost transparent by infrared.

Fowler and Harlow obtained good detail in the infrared photomicrography of wood sections, using Neocyanine as a stain, and infrared film having its maximum sensitivity at about 8,200 Å. Neocyanine gave better results than stains such as Heidenhain's iron alum-hematoxylin.

In 1934 Prát and Hrubý²⁴ stated that insufficient material was available for definite conclusions to be drawn in the instances in which infrared photography would have special applications. Their illustrations showed, nevertheless, that in photomicrography through whole leaves very useful results were obtained in the case of cells with colored relatively opaque or thick membranes and cells with many and large plastids. The infrared also showed advantages in experiments with vital stains.

In many of the papers which have been published on infrared photomicrography, illustrations are given comparing the results obtained by the infrared with those given by the normal technique in green light. A few papers do not give any such comparison, which is to be regretted, because the advantages in the use of the infrared are not apparent to the reader. In fact, in some instances it would be desirable to compare the infrared photographs with those obtained by visible red light.

In order to illustrate the results obtainable by infrared photomicrography, some photographs are reproduced in Figure 59. They were kindly provided by Professor Prát, of the Karlov University, of Prague. The conditions of taking them were as follows:

Hegener camera, 400-watt Wotan-Nitra projection lamp, Zeiss apochromat 10, Zeiss K20 ocular, plate 23 cm from ocular.

(a) *Epithemia turgida*. Living. René Ortho-Iso plate, no filter, 1 second exposure.

(b) The same. Agfa Infra-red plate 810, Agfa 84 infrared filter, 20 seconds exposure.

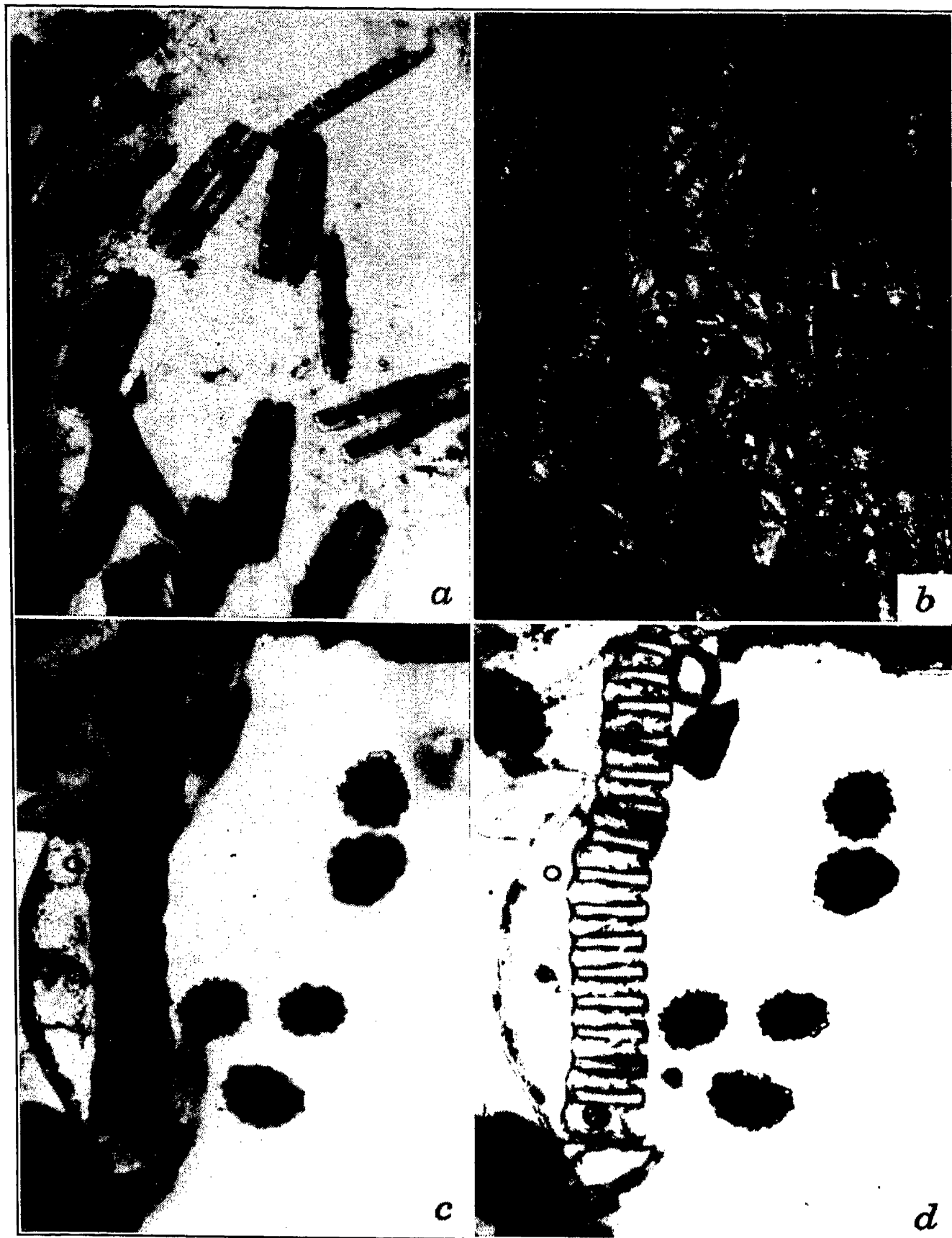


FIG. 59. Photomicrographs by visible and infrared radiation. For details, see text.

(Courtesy S. Prát)

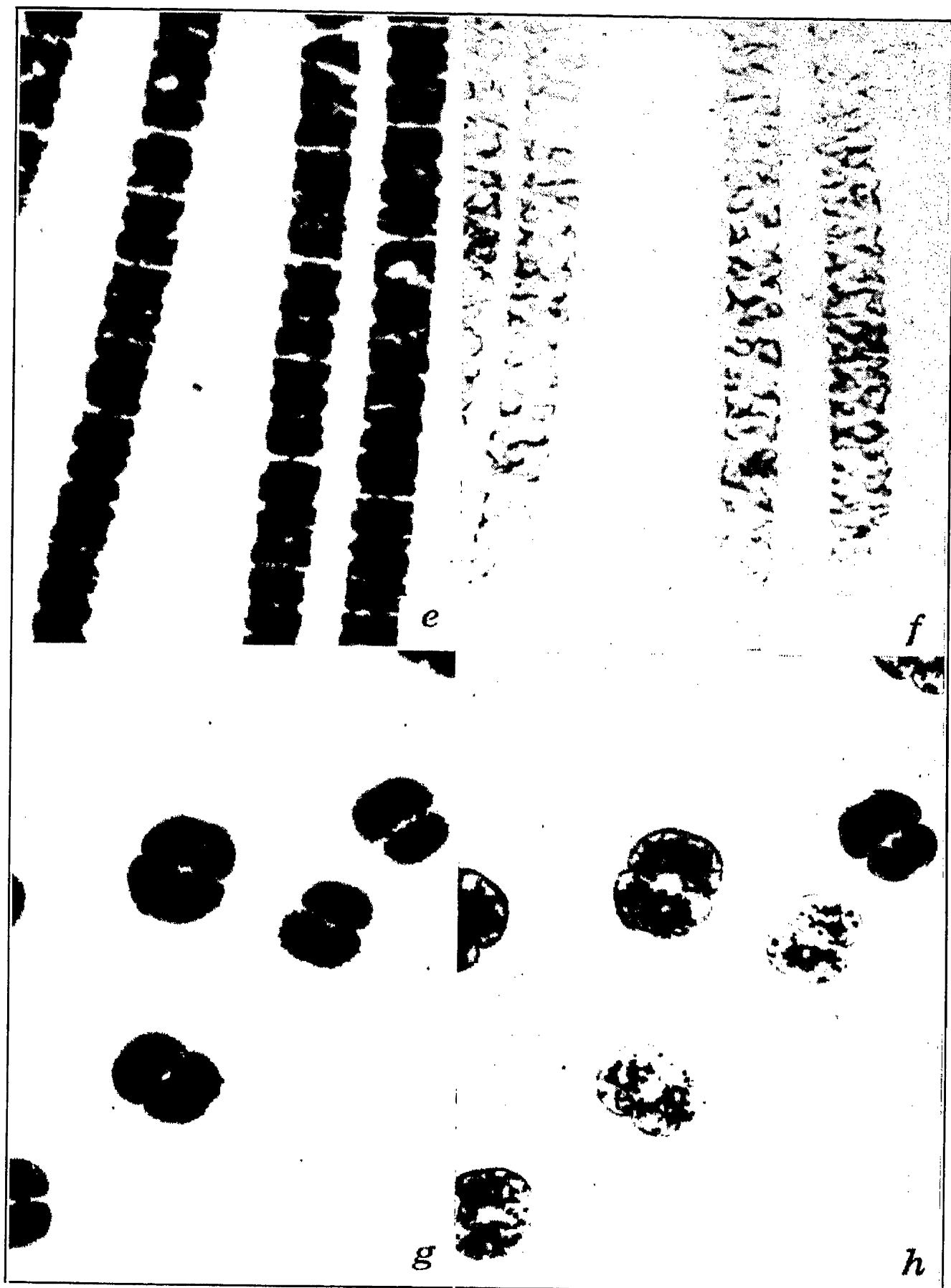


FIG. 59 (Continued).

(c) *Ceterach officinarum*. Sporagium. Living. René Ortho-Iso plate, Zeiss medium-yellow filter, 2 seconds exposure.

(d) The same. Agfa Infra-red 810 plate, Agfa 84 infrared filter, 20 seconds exposure.

(e) *Spirogyra* sp. Living. René Ortho-Iso plate, no filter, 8 seconds exposure.

(f) The same. Ilford Infra-red plate, Zeiss infrared compound filter, 100 seconds exposure.

(g) *Cosmarium botrytis*. Neutral red vital stain. René Ortho-Iso plate, no filter, 10 seconds exposure.

(h) The same. Agfa Infra-red 810 plate, Zeiss infrared compound filter, 100 seconds exposure.

Some references to infrared photomicrography of coal sections are to be found in Chapter X.

INFRARED PHOTOMICROGRAPHY OF TEXTILE FABRICS

In the section of this book dealing with the applications of infrared photography in the textile industry (Chapter VIII, p. 178), attention is drawn to the advantages of the infrared in examining fabrics dyed in dark colors. These are particularly important in the photomicrographic study of fibers and structure, in which black and brown dyes actually may prevent recognition of detail by visible light. Most dark dyes are transparent in the near infrared, and the use of this radiation enables a dark cloth to be studied with the ease of undyed material. In dyed wool the scales and other structural details can be revealed. The effects of chemical finishing treatment of fibers can be studied. By way of illustration of the technique, the method employed in the Kodak Research Laboratories will be described. Some of the photographs obtained are reproduced in Figure 60.

A Silvermann illuminator is chosen for the illumination of the cloths since it or a similar type of illuminator is widely used in textile photomicrography, and it affords the fastest and simplest method of setting up the illumination. A focused beam of light from a ribbon-filament lamp is added, with the beam making an angle of about 20° to the plane of the cloth in order to bring out the contours of the weave and remove the very flat appearance which is obtained otherwise. Any focusing lamp is suitable for

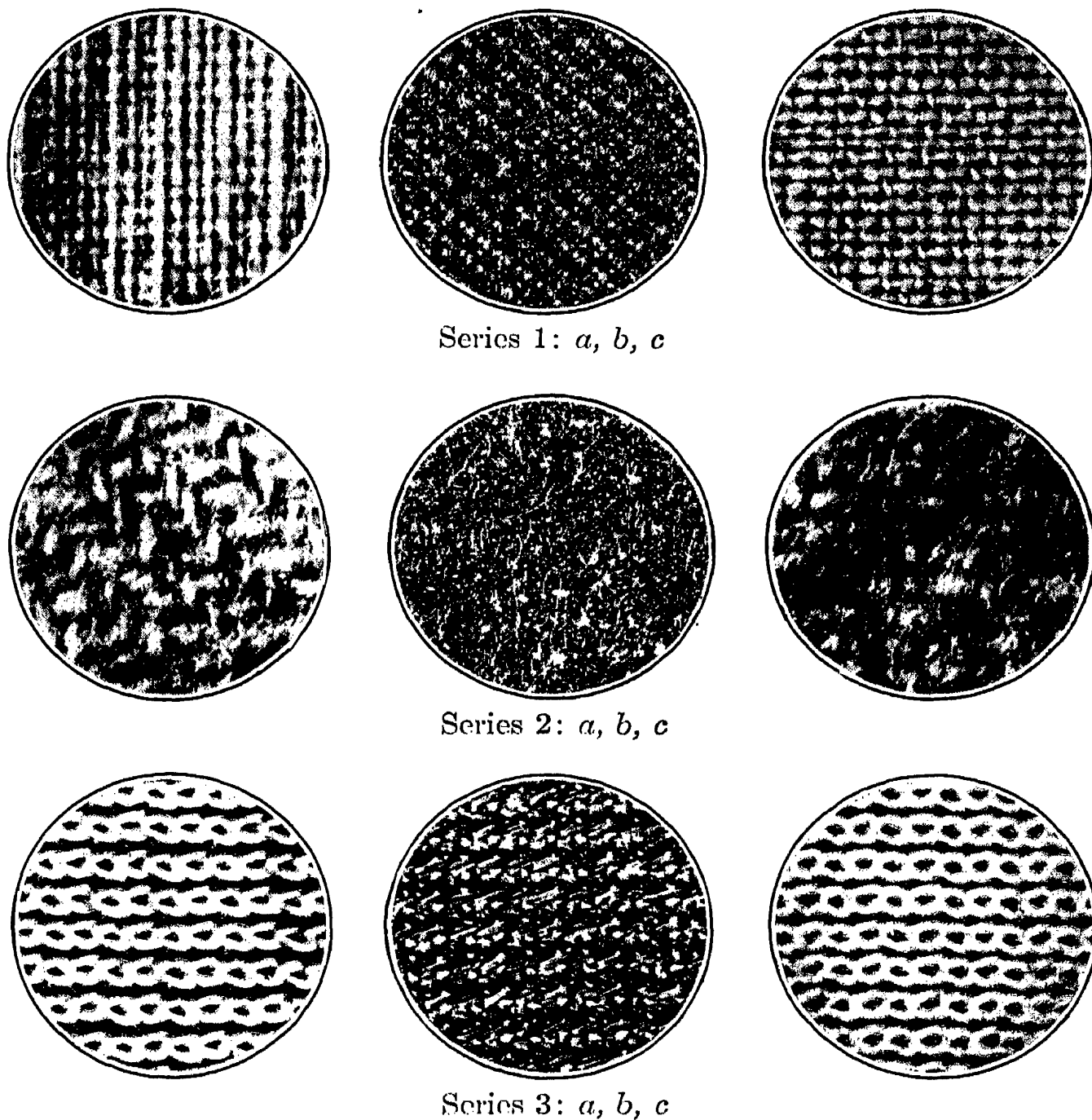


FIG. 60. Photomicrographs of white and black cloth by visible and infrared radiation.

Series 1: *a*, white cotton, by visible light; *b*, same dyed black, by visible light; *c*, as *b*, by infrared.

Series 2: *a*, white wool, by visible light; *b*, same dyed black, by visible light; *c*, as *b*, by infrared.

Series 3: *a*, white cellulose-acetate knitted cloth, by visible light; *b*, same dyed black, by visible light; *c*, as *b*, by infrared.

the purpose, and, if the intensity of the auxiliary beam seems to predominate, it can be reduced readily by neutral-density filters. Control of the background is very important in the photomicrography of cloth. It should afford a decided contrast with the cloth and will thus vary with the color of the cloth. White cloths are usually laid on a sheet of matte black paper. Darker cloths are treated differently; they are laid on a piece of ground or opal glass, and a transmitted beam of light is focused on this glass in the usual manner for photomicrography by transmitted light. By varying the intensity of the transmitted beam compared with the illumination above, the background may be made any desired brightness to furnish optimum contrast to the cloth. When infrared illumination is used by reflection, a blotter soaked in the infrared-absorbing dye Naphthol Green is used in place of the black paper background.

In Figure 60 are shown photomicrographs made in the manner described. The subjects are cotton, wool, and cellulose acetate cloths. In each series are photographs of the undyed white cloth by visible light, and of the same cloth dyed black, by visible and infrared. The details are as follows:

Series 1:

- (a) White cotton cloth, oblique illumination ($15-20^\circ$), 48-mm Micro-Tessar, $f/8$, no filter, Wratten Panchromatic plate.
- (b) Same cloth dyed with National Erie Black N. R. Extra (Schultz VII-628), oblique Silvermann plus 20° beam plus transmitted, 48-mm Micro-Tessar, $f/8$, no filter, Wratten Panchromatic plate.
- (c) Same as (b), oblique Silvermann plus 20° beam, 48-mm Micro-Tessar, $f/8$, Wratten no. 87 filter, Kodak Infrared-Sensitive plate. Background, blotter soaked in Naphthol Green.

Series 2:

- (a) White wool cloth, oblique Silvermann plus 25° beam, 48-mm Micro-Tessar, $f/8$, no filter, Wratten Panchromatic plate.
- (b) Same cloth dyed National Chrome Black F (Schultz VII 614), oblique Silvermann plus 25° beam plus transmitted, 48-mm Micro-Tessar, $f/8$, no filter, Wratten Panchromatic plate.
- (c) Same as (b), oblique Silvermann plus 25° beam, 48-mm Micro-Tessar, $f/8$, Wratten no. 87 filter, Kodak Infrared-Sensitive plate. Background, blotter soaked in Naphthol Green dye.

Series 3:

- (a) White acetate knitted cloth, oblique Silvermann plus 20° beam, 48-mm Micro-Tessar, $f/8$, no filter, Wratten Panchromatic plate.
- (b) Same cloth dyed National Nacelan Black B, oblique Silvermann plus 20° beam plus transmitted, 48-mm Micro-Tessar, $f/8$, no filter, Wratten Panchromatic plate.
- (c) Same as (b), oblique Silvermann plus 20° beam, 48-mm Micro-Tessar, $f/8$, Wratten no. 87 filter, Kodak Infrared-Sensitive plate. Background, blotter soaked in Naphthol Green dye.

Spectral transmission measurements made on the three black dyes showed that they all transmitted fully in the region about 8,000 Å.

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Chapter XII

SPECIAL APPLICATIONS OF INFRARED PHOTOGRAPHY

Many applications of infrared photography are of such importance that whole chapters in this book have been devoted to a treatment of them. In this chapter consideration is given to some of the uses which have not been discussed fully elsewhere. It should be read in conjunction with those chapters which concern the general practice of infrared photography (Chapter II), photographic darkroom practice (Chapter III), the characteristics of materials (Chapter IV), and the sources of infrared radiation (Chapter VII).

A subject which is of outstanding interest is the photographic penetration of haze. Its understanding is basic to the use of the infrared in landscape photography, survey work, reconnaissance, and so on. Chapters XIV and XV have, therefore, been devoted to its detailed consideration. In order that the photographer shall not be confused by a mass of detail, however, the practical aspects of haze penetration are dealt with here. The fuller study, important for the best understanding of the practice and its limitations, has been relegated to a later section of the book.

GENERAL LANDSCAPE PHOTOGRAPHY

A very popular application of infrared photography is photographing landscapes. The special effects which it produces can be obtained with the ease of ordinary photographs and have an appeal as a consequence of their striking contrasts and their clear rendering of the detail of distant objects. The chief characteristics of infrared landscape photographs are as follows:

Haze is penetrated so that hills and distant detail, which might otherwise be flattened, are rendered sharply. This natu-

rally eliminates the "atmosphere" which many photographers consider desirable in a landscape photograph.

Grass and the leaves of deciduous trees are generally rendered very light, as if they were covered with snow. Coniferous trees usually reproduce darker.

The sky is very dark, particularly away from the horizon, although the darkening also depends on the angle of the sun in relation to the camera; it is more noticeable as the camera is pointed away from the sun.

Clouds appear white. Heavy clouds, such as the cumulus variety, stand out strikingly against the dark sky. Lighter and higher clouds, such as cirrus, may be made to show up against the dark sky when they are invisible in an ordinary picture.

Shadows are very dark, particularly if the sky is clear so that they are illuminated only by scattered blue skylight.

Water generally reproduces as black.

Most of these characteristics are evident from the photographs in Figure 61, which show a landscape photographed on an ordinary non-color-sensitive film, a panchromatic film with a yellow filter (reproducing the tones in the relative values as seen by the eye), a panchromatic film with a red filter, and an infrared plate with a red filter.

As far back as 1890 O. N. Rood (see p. 361) published curves showing the high reflectivity of leaves in the extreme red, but the first photographs appear to be those made by Wood¹⁵⁰ and shown in lectures before the Royal Photographic Society in 1910 and the Royal Institution in 1911. He used the Wratten Panchromatic B plate, which was made for the spectroscopy of the extreme red and which was sensitized by a special method with Pinacyanol, and a filter compounded of dense Cobalt Blue glass and a solution of potassium bichromate. The exposure in bright sunlight was several minutes at $f/8$. With the film available at the present time, the exposures would be of the order of $\frac{1}{25}$ second at $f/11$.

Too much emphasis cannot be placed on the important contributions which Wood made to the knowledge of infrared photography. His pioneer work is scarcely ever mentioned in publications on photography by invisible light; yet most of the characteristics of infrared photographs which are well known at the

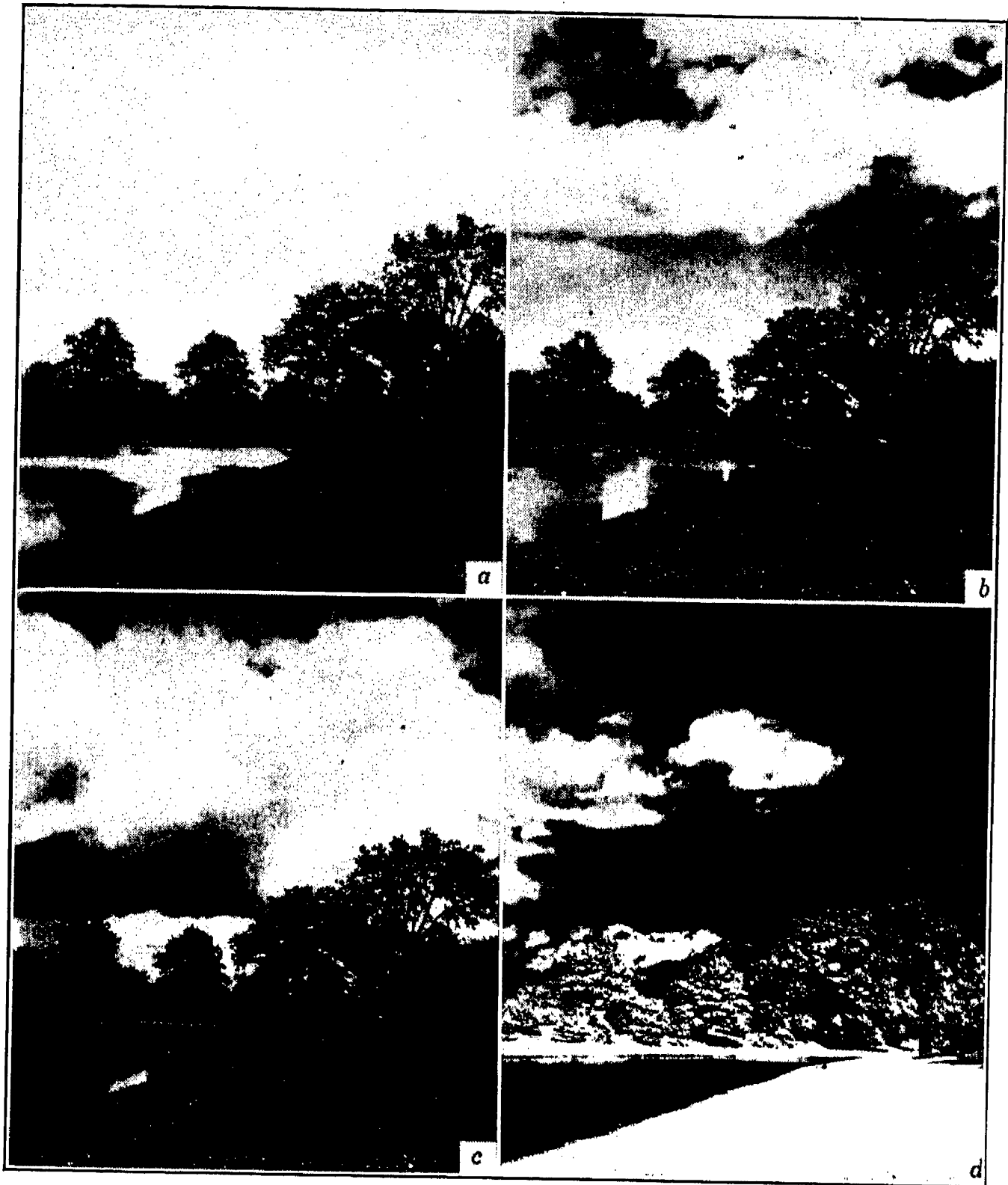


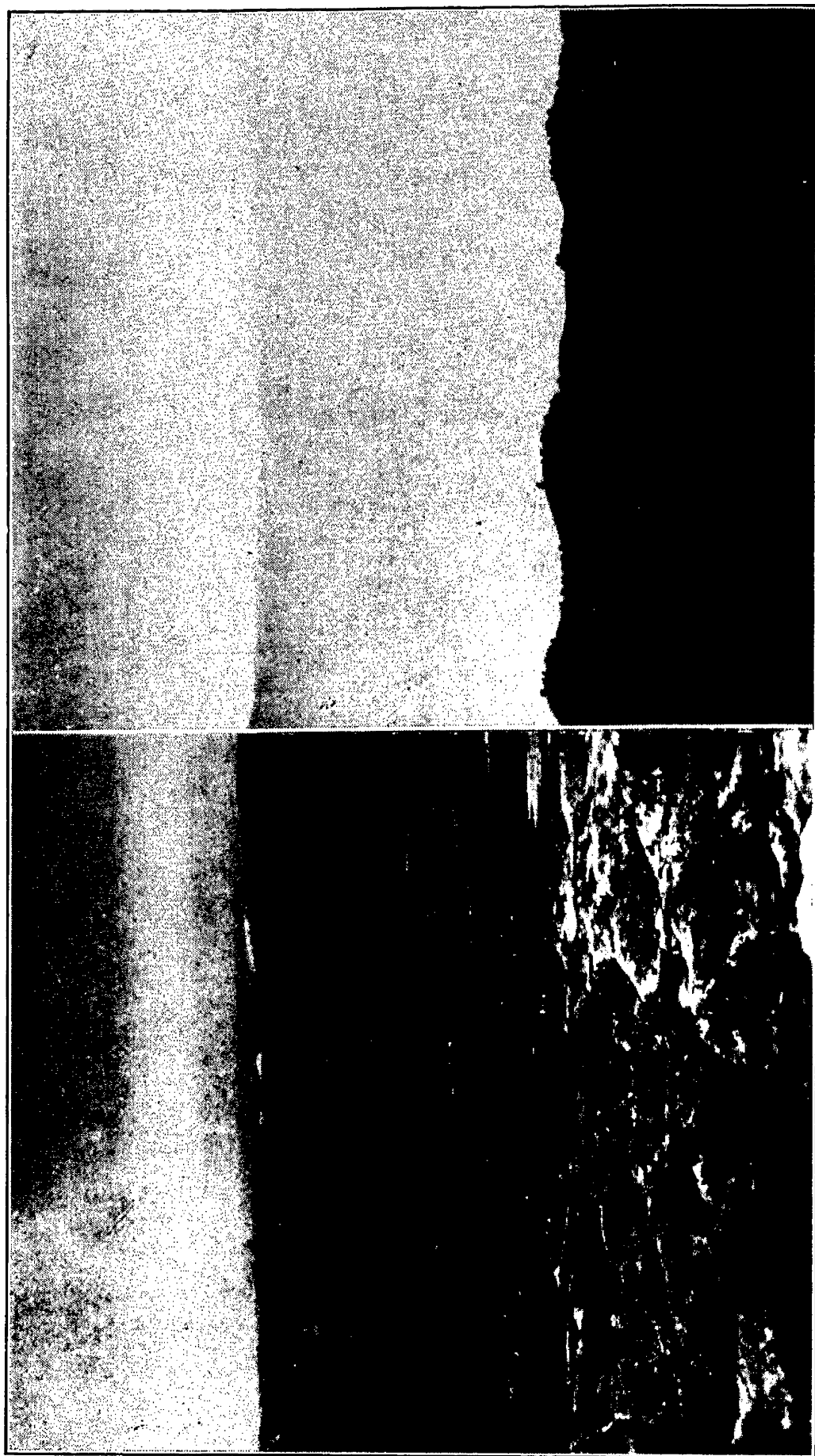
FIG. 61. Photographs of landscape by visible light and infrared. Photograph *a* was made on an ordinary non-color-sensitive film; *b*, on a panchromatic film through a yellow filter; *c*, on a panchromatic film through a red filter; *d*, on an infrared plate through a red filter.

present time were clearly shown by him in 1910 and 1911. They were entirely overlooked by the journalists who acclaimed as great discoveries the infrared pictures made 20 years later.

The earliest long-distance photographs which showed the superiority of the infrared in penetrating atmospheric haze were made in 1924 by Wright,¹⁵⁷ at the Lick Observatory. They revealed the Sierra Nevada Mountains in the neighborhood of the Yosemite Valley at a distance of 135 miles. The pictures were made from the Observatory, which is situated on Mount Hamilton on the Coast Range in California. A pair of them, reproduced in Figure 62, shows the scene as it appeared by violet light and to the camera provided with an infrared plate.

PHOTOGRAPHIC SURVEY FROM THE AIR AND GROUND

In survey by means of photography, the camera replaces or supplements the instruments employed in the normal methods of survey. The photograph itself is a substitute for the sketch or plot which the surveyor would otherwise make, and it must carry such information as will enable him to plot an accurate map in the office. At the present time, the photographic camera is one of the most important instruments of the surveyor of large tracts of country. It may be operated from the ground or from the air. In the case of ground photography, it is important that the places from which the photographs are to be taken must be relatively easy of access and they must not change their positions. Limitations to the usefulness of ground photography in surveying exist in the difficulties of securing adequate views of flat or enclosed country, and of moving across some kinds of country in order to find enough stations from which the photographs can be made. Photography from the air, on the other hand, enables the photographer to get well above the district to be surveyed so that his field is not obscured by surface details. It requires the minimum of ground stations to be used for control. An aerial negative properly made reveals the details of the surface very clearly, and, if pairs of photographs are used in a stereoscope, the relief of the surface may also be studied and plotted. There are, naturally, certain difficulties presented by aerial photographs themselves. In the survey of ground covered with dense forest, for instance, it may not be possible to map small detail in the



A

B

FIG. 62. Photographs of the Sierra Nevada Mountains in the neighborhood of the Yosemite Valley, from the Lick Observatory on Mount Hamilton, on the Coast Range.

Photograph A was made by infrared, and B by violet light. The Yosemite Valley lies to the middle left, and is nearly 120 miles from the viewing point. The crest of the Sierras is 135 miles distant.

(By W. H. Wright)

ground underlying the trees. In making and interpreting aerial photographs as compared with those made from the ground, account must be taken of the fact that the camera is moving continuously, that it may vary in its speed and height, and that it may be tilted.

It is evident that both ground and air photographs possess a great advantage in that they provide a permanent record which may be taken to the laboratory for the purposes of measurement and the plotting of maps. Moreover, in a single exposure, they record minute detail which could not be obtained by the normal methods of survey and sketching. The science of photogrammetry has been developed to deal with the making of maps from photographic records and, if it is properly applied, results of great precision are obtained. The photographs are used for measuring the bearing and angles of objects, their distance, and their heights. In all cases, it is necessary that they should show the maximum of detail—which should not be rendered difficult to recognize through distortion of the tone values of objects—and that the orientation of the camera and its optical constants be accurately known.

One of the main obstacles to the satisfactory rendering of detail is presented by aerial haze. This can be eliminated to a large extent by photographing by yellow, red, or infrared radiation, the selection depending on the density of the haze.

In wartime, by far the greatest part of the knowledge of the enemy is obtained through aerial photographs, and special photographic reconnaissance units are formed to take the vast numbers of photographs required. Although most of them are made on fast panchromatic film, infrared film forms an important accessory for haze penetration and camouflage detection (see page 355).

GROUND PHOTOGRAPHY

Some of the requirements and limitations of ground photography have already been mentioned. Special survey cameras are employed which have means for orienting them precisely in relation to the subject, levels for setting them true to the perpendicular, and means for properly orienting the image inside the camera. Photographs are taken in pairs from the ends of measured base lines, in such a way that the same object can be iden-

tified on the two photographs. The method is particularly applicable in mountainous country, and the photographs may be used for supplying detail in conjunction with existing maps, for revisions of such maps, and for the preparation of new ones.

Since the position of the camera is fixed in relation to the subject photographed, the exposure may be as long as desired, provided there is little wind. Small lens apertures may therefore be used to give a great depth of field, and the exposures may be made with feeble illumination. Plates are used, because they undergo no dimensional change when processed, and their weight is rarely a disadvantage. Films have the advantage of portability and may be employed when an expedition is likely to be away from its base for a long time or when transportation is difficult.

Panchromatic materials are commonly used with a yellow filter to penetrate haze. Better penetration is obtained with a red filter, and with thick haze the best results are obtained with infrared-sensitive materials. In rendering distant mountains and in sharpening the horizon infrared photography is unsurpassed. The influence of haze is particularly noticeable in telephotography of mountain ranges at long distances, and the value of the infrared in such cases has been appreciated by surveyors. Attention has been drawn to its advantages by Choffat,²¹ in connection with his large-scale telephotographic survey of Mont Blanc from a distance of 85 kilometers.

The Survey Branch of the Department of Lands of the Province of British Columbia has made a special study of the suitability of infrared photography for survey work, and the following comments were kindly provided by the Surveyor General. Infrared photography appears to be superior to panchromatic photography for views under the bright sun and for photographing into shadows early or late in the day. In the absence of appreciable smoke or haze, when the light is patchy and shadows of clouds abound, panchromatic materials often have an advantage, however. The infrared can usually be considered most suitable when appreciable haze is present, although there are cases where the greater distance rendering obtained by it may actually be a disadvantage. This is so, for instance, when there are ridges and hilltops to be located below the skyline. There

is a tendency for these to be concealed if the haze is efficiently cut. Deciduous trees and grass are rendered white in infrared photographs, so making it difficult at times to distinguish between shadows and areas of trees. Conifers usually appear dark and can thus be separated from deciduous trees but not necessarily from other dark objects. Brush, which sometimes borders meadows, photographs light like the grass, so that the edge of a meadow may be difficult to identify, while bluffs in timber can usually be distinguished more readily in panchromatic photographs. In the photography of highly mountainous country where there is not much vegetation, infrared plates and films are generally superior to panchromatic materials. It is mainly in open grassland with deciduous growth that the infrared will be of little value if the detail desired is dependent on the vegetation.

The ideal plate for topographic work should have a moderately high speed so that the exposures would not be unduly long in dull or windy weather and very high resolving power so that it could render minute detail. It should not give too high a contrast with a few minutes' development; it should be backed to reduce to a minimum the effects of halation, and it should be sensitized, that is, orthochromatic, panchromatic, or infrared. Unfortunately, in practice, high resolving power is usually associated with low speed and high contrast, and so it is necessary to compromise by selecting a plate rather low in speed and of fairly high resolving power and contrast. From a study made in the Zeiss Laboratories, it was found that, of the plates commercially available, those used for lantern slides had the most desirable characteristics, although it was pointed out that if it could only be made sufficiently fast, the Taupenot collodion-albumen plate would be ideal for resolving power. The common sensitizings for the near infrared, ranging from 7,000 to 8,500 Å, are generally satisfactory (see pp. 87-90, 445).

AERIAL PHOTOGRAPHY

Aerial photographs are made in special cameras properly mounted in airplanes to ensure the desired field of view and to minimize vibration. Film is invariably used, because it is much lighter than plates, and since it is loaded in long rolls it can be changed much more rapidly so that series of pictures can be

made in quick succession. It is necessary to do this, because the airplane with its camera is continuously moving in relation to the subject, and it is important for topographic work that there be an overlap between the record on one negative and that on the next. At the present time, aerial film is available on regular and so-called "topographic" support, which has a minimum of dimensional variation. If the shrinkage of film on processing is equal in the length and width it is of relatively little import. It is, however, a serious matter if it is greater in one direction than in another, because it is difficult to compensate for it in making maps from the negatives. In the present types of topographic support, however, the shrinkage is very low and essentially equal in both the width and length of the film. Such film should always be selected for precise work. Both regular and topographic films are made on nitrate and "safety" supports, although by far the bulk is of the second type.

Since the aerial camera is moving in relation to the subject photographed, the exposure must be kept short so that blurring of the image can be avoided. The maximum permissible exposure time depends on the speed of the airplane and its height. The maximum lens aperture employed is up to $f/2.5$, and the maximum exposure time about $\frac{1}{50}$ second. By flying high and with proper maneuvering of the airplane it is possible to increase this time. In rare cases, exposures have actually been made in one-fifth second from heights of over 20,000 ft. The short exposures which must be used in aerial work require that the film be very sensitive to light, and it is not possible to use slow fine-grained materials of high resolving power which might be desirable in certain instances and which could be used in ground work. An exposure time of about $\frac{1}{150}$ second will generally be used, and the widest-aperture lenses are not needed for survey work. In low-altitude reconnaissance from fast-moving aircraft, exposures of $\frac{1}{500}$ second or less have been used.*

Aerial photographs are sometimes made as an end in themselves either for pictorial and economic purposes, for military use, or for other objects where a knowledge of the features of

* In some modern aerial cameras in which the film is moved to compensate for movement of the image, effectively longer exposure times can be given.

the ground is desired. They also provide supplements to maps, and are very important adjuncts to maps which are old or inaccurate. They are also used extensively as a basis from which accurate new maps may be drawn.

There are several types of aerial photographs, classified according to the manner in which they are made. The two main kinds are known as "verticals," in taking which the camera is pointed vertically downwards, and "obliques," in which case the camera is deliberately pointed at an angle to the vertical. In making the so-called "high obliques," the axis of the camera is inclined in such a manner as to include the horizon in the picture, while all other oblique photographs are called "low obliques." In order to cover a large area of ground systematically, and to provide pairs of photographs which may be viewed in a stereoscope to show relief, exposures are made at regular intervals while the airplane is flying in a straight course. The result is known as a "strip," and the successive photographs usually overlap to the extent of 60 per cent. Strip photographs may be assembled and the overlapping parts cut away to provide a "mosaic" of a single strip of territory, or of a broad area if a number of adjacent strips are assembled. So-called "composite verticals" are made by using a number of cameras, or single cameras provided with more than one lens and roll of film, to make verticals and obliques simultaneously. Multiple-lens cameras have been developed with three, four, and five lenses, and the Coast and Geodetic Survey in the United States actually had a camera provided with nine lenses. Such cameras naturally cover a much greater area of ground than those using a single lens.

During the Second World War there was developed a system of aerial photography for mapping in which three wide-angle cameras were used simultaneously, and known as the trimetrogon method. One camera made vertical photographs while the other two took obliques laterally, including the horizon on each side and overlapping the central vertical picture. The flight lines could be as much as 40 miles apart, the actual distance depending on the scale of the final map, and a large amount of territory could clearly be covered in a few hours' flying. Another type of aerial camera developed in the war was one in which the film

moved continuously at a rate intended to compensate for the travel of the image of the ground, the picture being made through a narrow slit in front of the film. In other cameras designed to give sharper pictures by compensating for the movement of the image, the lens is moved, or the film is moved slightly, during the actual time of exposure.

In order to permit accurate interpretation of aerial photographs for mapping purposes, data are recorded which show the height and speed of the airplane, the direction of flight or orientation of the camera in relation to true north, the tilt of the camera, the focal length of the lens, the date, time, location, and so on. For information on the methods of making maps from such aerial photographs, which is outside the scope of this work, the reader should refer to some of the publications on photogrammetry.

The purpose of an aerial photograph, except in those cases where it is made purely for pictorial effects, is to record the detail of the subject so that it can readily be identified and interpreted. The principles are those necessary for all photographic record work, although atmospheric haze provides a disturbing factor. Vertical photographs generally show an appreciable loss of detail and flattening of contrast due to this cause, when made from heights above 5,000 ft, whereas at altitudes of 10,000 ft or more the haze effect is frequently so marked that it is exceedingly difficult to distinguish ground detail in the photograph. From these high altitudes, taking long-distance obliques is almost impossible without taking precautions for the elimination of haze.

Most aerial photography is done on film of the type of Kodak Aerographic Super-XX Film, which is a high-speed film having more red sensitivity than panchromatic films for general use. It is invariably used with a yellow or red filter, the most common being the Wratten nos. 12 and 25. At the time of this writing, infrared aerial photography is done on fast films which are almost of the speed of the Super-XX. In the United States the only infrared aerial film is the Kodak Aerographic Infrared Film, the spectral sensitivity of which is shown in Chapter V. The common filter used with this film is the Wratten no. 25, although for some years prior to 1944 the no. 89A was standard in the Army Air Forces.

All lenses are not in good focus for infrared when they are in focus for photography with panchromatic film (see Chapter II). For best definition it may be necessary to apply a correction. The poorer definition of infrared pictures, even after refocusing, is usually ascribed to the fact that in design a lens is color-corrected for the visible and would therefore be unsuitable for the infrared. It has sometimes been suspected that infrared films are inferior from the point of view of granularity, resolution, or turbidity, and that this accounts for the poorer definition, but so far there has been no evidence deduced that it is inferior in these qualities to the normal panchromatic film.

The ability of the infrared to penetrate haze has never been shown better than in series of photographs made by Lieutenant Colonel A. W. Stevens, of the United States Army Air Forces. In one of them, Mount Shasta, in California, was photographed from a distance of 331 miles. At this distance the mountain was quite invisible, owing to atmospheric haze, and the camera was oriented by compass. The airplane was flying at a height of 23,000 ft, and the negative was made on Eastman Infra-red Aero Film (1933), hypersensitized, with an exposure of one-fifth second at $f/5$, through the Wratten filter no. 89A. Another photograph (see Figure 63) was made from the National Geographic Society-United States Army Air Corps stratosphere balloon, *Explorer II*, on November 11, 1935, from a height of 72,395 ft.⁹⁸ The ground horizon is about 330 miles from the camera, and the dust horizon above it marks the boundary between the upper and lower air, which is shown by the sharp change from dark to light in the photograph. The dust horizon is concentric with the earth's surface and clearly reveals its curvature. This picture was made with a Kodak $f/5$ lens of 304-mm focal length. On Eastman Infra-red Aero Film (1935) and a red glass filter, the exposure was $\frac{1}{25}$ second. The flight report showed that of the many photographs taken the best were on infrared film.

Many other infrared photographs have been taken which have helped to form public opinion as to the importance of infrared photography. They include a very fine series made over England on Ilford Infra-red plates by the London *Times*, and others taken on the Houston-Mount Everest flight,¹⁸ and by Bradford Wash-

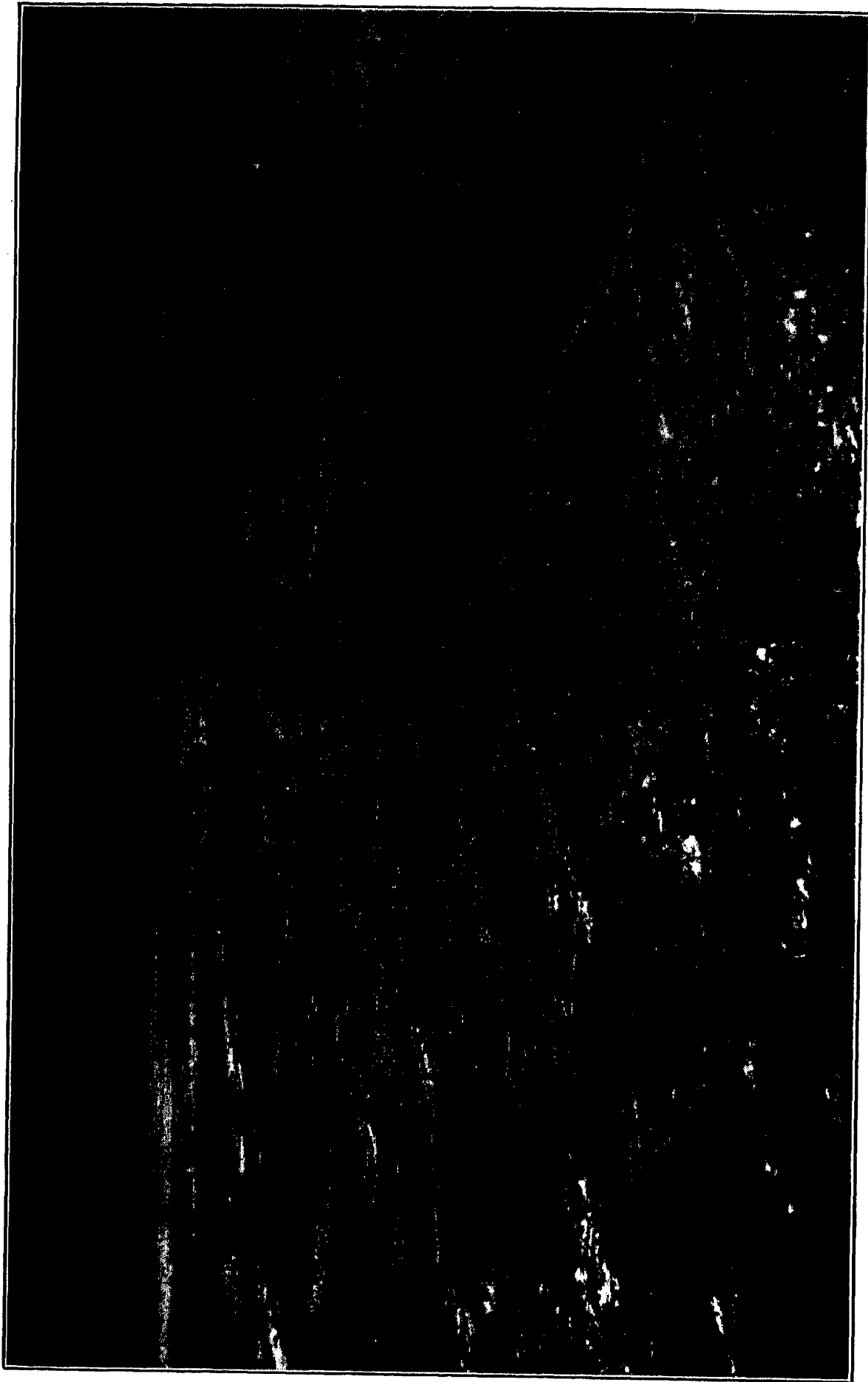


FIG. 63. Infrared photograph from an elevation of 72,395 ft showing the curvature of the earth and the division between the troposphere and the stratosphere. The balloon was at the highest point ever reached by man.

(Courtesy U. S. Army Air Forces and National Geographic Society)

burn, Jr., in Alaska. On many long-distance exploration flights, cameras are now provided with infrared film in addition to the panchromatic variety.

Some of the factors involved in carrying out aerial survey have already been mentioned. The chief use of the infrared is in penetrating haze which is too dense to be overcome by panchromatic materials and filters. Infrared photographs show a number of other characteristics, some of which may offer advantages and others disadvantages to the surveyor. On the whole, the horizon is rendered most clearly when photographed away from the sun. Lakes are usually reproduced as quite black in infrared photographs, which are superior to panchromatic photographs in showing water away from the sun; there is extreme contrast between the water and the shore line. In the infrared photography of terrain which is dotted with small lakes, as in Canada, there is sometimes difficulty in distinguishing between lakes and the black shadows of small clouds. The white rendering of grass, scrub, and foliage by infrared sometimes makes it difficult to identify them or to distinguish one from the other, although naturally some help is obtained from the shadows. Shoals under water do not show up. The complaint has sometimes been made that the lack of detail in the shadows in infrared photographs makes reconstruction difficult.

It is not possible to generalize about the usefulness of infrared photography in survey. Much must depend on the experience and judgment of the operators. Interpreters have become so very highly skilled in reading panchromatic photographs that, unless a very special advantage were to be gained by the use of infrared, they would not add to operational difficulty by insisting that infrared photographs be made in addition to panchromatic ones. In wartime, everything would be photographed on panchromatic film in any case, and there might not be the possibility of making duplicate exposures on special films, without flying special missions. For camouflage detection special photographs might be made, and there are also some peacetime purposes which demand the use of infrared. We shall go into camouflage detection and forest survey by infrared photography in detail in subsequent sections.

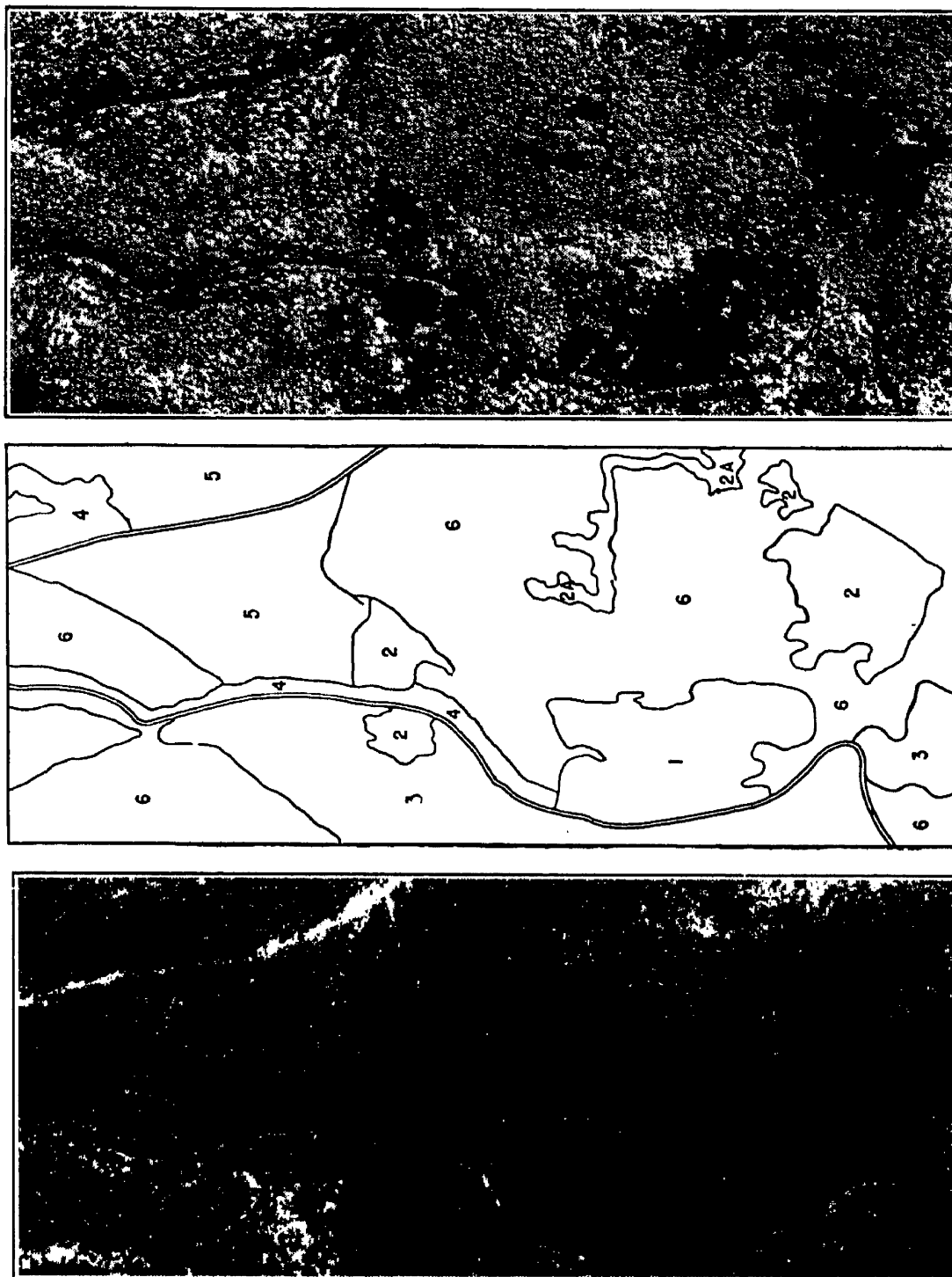
AERIAL FOREST SURVEY

The following notes on the use of the infrared for forest aerial photography were supplied by Stephen H. Spurr, assistant to the director of the Harvard Forest. They are based on a study of aerial photographs of the Harvard Forest, Petersham, Mass., and of an area near Albemarle Sound, N. C., taken by the Fairchild Aerial Surveys, Inc.; and an area in central Quebec photographed by the Royal Canadian Air Force. Forestry survey from the air is still in its infancy, and later experience may require some modification of the conclusions.

If the forester is to obtain the maximum benefits from aerial photographs, he must be able not only to use them for map purposes, but also to measure the dimensions of the individual trees on the photographs and to distinguish the various species. Photographs taken on panchromatic film are not satisfactory in that the various kinds of trees cannot ordinarily be distinguished on them. Infrared photographs, on the other hand, permit species differentiation to a considerable extent (see Figure 64).

Infrared aerial photographs of forest areas have been made using Kodak Aerographic Infrared Film and three different filters: the Wratten no. 12, which is yellow, the red Wratten no. 25, and the very deep-red Wratten no. 89A. In the case of most of the photographs discussed here, the flying height was 8,100 ft, and the scale 1:12,000. Definition was best with the no. 12 filter, and poorest in the case of the no. 89A. It is possible that this is due in part to the change of focus of the lens with wavelength and also to the fact that the lighter filters permit the use of smaller stops. The contrast and tone differentiation were best with the no. 89A filter, but were quite adequate with the yellow filter. In fact the yellow-filter results were easier for the average observer to interpret than those obtained with the dark filter. The contrasts were lower, because the bright-infrared reflectance of some foliage is toned down by the red and green which is passed by a yellow filter.

In all infrared photographs, hardwoods were reproduced nearly white and softwoods grey to black. Various softwood species in Central New England could be distinguished on the basis of tone as follows:



1. White pine, old growth.
2. White pine, young growth.
- 2A. White pine, indicating old fence row.
3. Mixed white pine, hemlock, and hardwoods.
4. Hemlock.
5. Mixed hemlock and hardwoods.
6. Hardwoods.

FIG. 64. Differentiation of timber species by infrared photography.

The left photograph was made on panchromatic film, while the right photograph of the same area of the Harvard Forest was made on infrared film. The key between the photographs will enable the reader to differentiate among the types of growths and to see how readily some of them can be distinguished in the infrared photograph.

Red pine: Very dark, frequently black. Very easily distinguished from all other native softwoods. Ponderosa pine (western yellow pine) has much the same color. Scotch pine is very slightly lighter in color, but cannot be easily distinguished. Neither ponderosa nor Scotch pine normally occurs in the same region as red pine. It is probably a fairly safe assumption that hard pines throughout the world photograph very dark on infrared.

Red and black spruce: Spruce in bogs photographs dark grey. On upland sites which are drier, it is somewhat lighter in color. Infrared photographs taken in the Rangeley Lakes region of Maine indicate that balsam fir may photograph somewhat lighter than spruce, though both are considerably darker than the hardwoods. In central Quebec, black spruce photographs much the darkest of any species.

White pine: Medium to dark grey. Definitely lighter than the foregoing.

White spruce: Very similar in tone to white pine though somewhat lighter. These two species cannot be easily distinguished from each other except by their shape, except under ideal conditions. However, they do not occur together to any extent in any part of eastern North America.

Hemlock: Light grey, yet noticeably darker than any hardwood. Definitely lighter in tone than any of the foregoing.

Larch: Similar in tone to hemlock, though possibly a shade lighter. European larch is found only in limited plantations in the Northeast, and it may therefore be distinguished from hemlock which is seldom put out in plantations. Tamarack or American larch is largely confined to bogs of the North Woods and may be recognized by its occurrence on these characteristic sites.

Hardwoods: All species are always lighter than any of the softwoods on infrared photographs. There is no evidence, however, that any distinction may be made between any of the hardwood species, since such minor variations in tone as do occur are obscured by variations due to angle of sunlight, moisture in ground, and the like.

In the other forest regions studied, it was similarly possible to differentiate most of the major timber species.

Defoliated and dying trees appear as black on infrared photographs. A spectacular example of this was the 1944 gypsy moth defoliation in Petersham, Mass., which was easily recognized and located on aerial photographs. Defoliation, however, is just as obvious on panchromatic photographs where it appears as white as in infrared photographs. In both cases, the color effect is produced by the forest floor beneath being made visible as a result of the defoliation.

The older the tree, the darker it will appear on infrared photographs. The reason for this is not apparent as the foliage does not differ visibly between specimens of the same species at different ages. However, it may be a result of the more broken-up crowns of older stands absorbing more infrared than the smooth crowns of younger stands. In any event, the range of tones is wide. Very young white pine is so light in color, it cannot be distinguished easily from hardwoods, whereas old white pine photographs nearly as black as red pine. The segregations of tone described hold for trees of any one age, but care must be exercised in distinguishing between an old tree of one species and a young tree of another.

The amount of reflection from the sun affects the tone of foliage in infrared photographs. For instance, hardwoods on a south slope which faces the sun appear lighter than similar trees on a north slope which faces away from the sun. This variation in tone, however, is not great and does not appear to affect the accuracy of differentiation. The interpreter can easily be trained to discount tone variations due to sun angle. A series of steep oblique photographs of the same area taken into the sun, away from the sun, and at right angles to the sun, do not reveal any significant differences in tone or resolution.

The general conclusion to be drawn from the study is that infrared photographs are definitely superior to panchromatic photographs for forest-type mapping. When red filters are used, the results may not always show good resolution, although it appears to be adequate if a yellow no. 12 filter is used. The tone differentiation given by the yellow filter is generally sufficient, and the pictures are more readily intelligible to the untrained observer.

Hardwoods can readily be distinguished from softwoods on the basis of tone. This is probably universally true for all forest regions. Most of the softwoods can be distinguished from one another on the basis of tone which ranges from black for red pine to light grey for hemlock and larch. In distinguishing individual species, however, allowance must be made for the age of the tree, the angle of the sun, and other factors which affect the tone. In infrared photographs the shadows are very dark

and may be misleading to the casual observer besides obscuring some of the detail on the ground.

AERIAL GEOLOGICAL SURVEY

Geological surveys are generally based on topographic maps, because they enable the distribution of geological features to be shown, and the surface geology may be deduced from the topographic forms. The aerial photograph itself, however, may reveal characteristics from which deductions of geological importance can be drawn. For instance, from the surface relief it may be possible to appraise the limits and approximate character of rock outcrops, faults are frequently visible from the air, the vegetation often bears a direct relation to the nature of the subsoil, and rocks and soil of different colors may be distinguished in photographs from the air. Infrared photography may often be of advantage for differentiating between types of vegetation and between various kinds of soil and rock, which often show differing reflecting powers in the infrared. Sometimes, however, the infrared blackens rock outcrops in forest areas too much for geological interpretation.

FOG PENETRATION

Among the most fantastic claims which have been made for infrared photography is its alleged ability to penetrate dense fogs, thereby allowing ships to navigate with complete safety in the worst of weather and airplanes to land when the ceiling is zero. It was largely through claims of this kind that the public's imagination was played upon by writers in the popular press. The impression created still lingers, and so it is appropriate at this point to emphasize most emphatically that, according to both theory and practice, such claims are utterly without foundation. Although the infrared is immensely valuable in penetrating atmospheric haze, the chances of penetration decrease as the haze thickens into mist and the mist into fog. When a fog is dense enough to be a menace to navigation, it is impossible to increase visibility through it by means of infrared photography. Moreover, there seems to be no chance of doing it in the future, whatever strides research may make in perfecting infrared plates and films. It is probable, of course, that, with the great strides

which have been made in the application of electromagnetic radiations which are ultimately made to produce a visible image, some indirect photographic method of fog penetration may be worked out in the future. Even in these days when prophets fail, it seems perfectly justifiable to assert, however, that no direct method of photography can ever accomplish it (see Chapters XIV and XV).

SPECIAL-EFFECTS PHOTOGRAPHY

One of the earliest uses to which infrared-sensitive film was put was the simulation of moonlight effects by photographing in sunlight, in the motion-picture industry. Its use for this purpose was first described by Ball¹¹ in 1925. Using Kryptocyanine, he succeeded in sensitizing film so that it was fast enough to be used in a motion-picture camera. The moonlight effect is that which is typical of outdoor infrared photographs, which give dark skies, black shadows, and bright leaves and grass.

Imitation night scenes have been made in daylight by using panchromatic negative film and deep-red filter to overcorrect the sky, combined with underexposure to render the rest of the scene dark. This method is not very satisfactory, primarily because underexposure does not give good photographic quality. In addition, of course, scenes have actually been made at nighttime, using appropriate lighting. This, however, is undesirable for a number of reasons. For instance, there is a definite economical disadvantage, since there is considerable expense involved in the consumption of electricity, equipment, transportation, labor, and time, and there is a personal factor which enters, in that nighttime is an inconvenient time for the players to work, and a possible risk of illness is involved.

At the present time, infrared films are so sensitive and of such photographic quality that perfectly satisfactory night scenes can be obtained outdoors in sunlight. There are, naturally, certain effects which are best photographed in the customary manner, but according to Edouart³⁸ 50 to 70 per cent of the scenes can be made better and more efficiently by day. When infrared film is used and the contrasts are not exaggerated, there is no loss of shadow detail which must occur when the photograph is deliberately underexposed.

Papers describing the use of infrared film in producing night effects have been published by Edouart,³⁸ Hough and Leahy,^{65, 79} Kelley,⁷² and Dyer.³⁵ These articles describe the uses of the method in Hollywood practice.

In the production of night effects in daylight it is desirable to use booster lights or reflectors. According to Edouart, outlining rim effects produced by their means are very effective. The most pleasing results are generally obtained by using a cross lighting, or a modeled diffuse front or semifront lighting. Direct sunlight is not always necessary, and excellent results have been obtained with the players in the shade, by using reflectors or artificial front lighting. Street lamps and automobile headlights, flames and torches are rendered very realistically, and windows must be illuminated with artificial lights as in common practice.

The only alteration in make-up as compared with panchromatic photography is the use of a slightly darker lip rouge produced by the addition of a small amount of blue or brown pigment to the standard panchromatic lip make-up. The other types of make-up are rendered normally. A factor which cannot be ignored is the different reproduction of colored paints by infrared as compared with visible light. Paramount has overcome this by painting a scene with a blue-grey color which is equally effective for panchromatic and infrared photography. In order to avoid the excessive white appearance of foliage by infrared it is sometimes desirable to spray it with a paint which is photographically satisfactory.

In the field of still photography, very striking effects can be obtained by using the infrared, particularly with architectural subjects and street scenes if side or back lighting casting strong shadows is employed. Strong highlights against broad areas of shadows are very realistic. Effective shots can also be made over water, particularly if boats or light buildings appear in the picture. Snow-clad mountains are very suitable subjects. It is important in imitation night pictures that no clouds appear in the sky. These are rendered as very bright in the photograph, whereas clouds on a moonlight night actually appear relatively dark. Photographs made directly into the sun are very interesting, although care must be taken to use a hood so that the sun does not shine directly into the lens, so tending to flatten

the results. The effects of moonlight reflected in water, very attractive to some photographers, can be simulated in this manner.

The imaginative commercial photographer should be able to use infrared-effect photographs for producing very attractive results for advertising. The applicability is, however, much more limited for fashion work and portrait photography. The falsification of the relative tones of colored materials by infrared is sufficient to rule it out for most fashion work. In portraiture it is very rarely that the subject is desirous of bizarre effects or any distortion of the normal appearance. Actually, it is generally desired to enhance rather than to degrade the aesthetic aspect. In this, infrared is of no value at all. Portraits made by the invisible rays show the skin as if it were covered with white chalk. The eyes appear as small black spots, all wrinkles are accentuated, and an incipient beard is reproduced as if it were a stubbly growth. Much improvement can result from the use of make-up and appropriate lighting, but the results do not justify the trouble unless unnatural effects are wanted. In producing illustrations for magazines of the "thriller" type, the infrared might be used to terrifying advantage.

For special effects in still photography, the film sensitive in the near infrared between 7,000 and 8,500 Å may be used. There is generally no advantage in using the longer wavelengths, since the effects are not appreciably accentuated, and marked increase in exposure is necessary. The red filters listed in Table IV on p. 20 are all satisfactory.

COMPOSITE PHOTOGRAPHY

It has been proposed that the Herschel effect (see Chapter VI) be used in making composite photographs. According to the method of Planskoy,¹⁰¹ part of a negative can be fogged by means of white light, and a negative can be printed into the fogged areas by infrared which, through the Herschel effect, destroys the fogged image according to its intensity. Planskoy also proposed a method of making composite pictures using a background which reflects only infrared and not visible light. The subject is illuminated only by visible light and the background only by infrared. One photograph is taken only by infrared and a second

photograph only by visible light. With the two views so obtained, masks may be prepared for making composite photographs.

DAZZLE-FREE PHOTOGRAPHY

The dazzling effect of the bright white lights commonly used in photography can be a source of considerable disturbance to the subject, particularly if he is photographed while performing some function, and not deliberately posing in a studio. As far back as the days of the daguerreotype, it was realized that blue light was far more comfortable to the sitter than bright sunlight, and it was proposed that blue windows be used in the studio. This would not affect the exposure times but would protect the face of the subject against the bright light. With modern photographic materials of the panchromatic type, the use of blue glass over the light source would require a great increase in exposure. It has been proposed, therefore, that a filter be used which absorbs the yellow-green light, to which the eye has its maximum sensitivity and which, consequently, is responsible for much of the dazzling effect. Modern photographic practice, however, demands the use of panchromatic plates and films, and in their cases a green-absorbing filter would increase the exposure. Biehler and Fröhlich¹⁷ have therefore suggested the use of infrared-sensitive materials in conjunction with a filter, such as Cobalt Blue glass, Crystal Violet, Acid Rhodamine, or a mixture of these two dyes, which absorbs the green but transmits freely the violet and blue and the infrared.^{30, 37} The loss of effective sensitivity in the green is compensated for by the sensitivity in the infrared. It is stated that the exposure time is not appreciably increased, and that the tone rendering is satisfactory, whereas the visual brightness of the source is much diminished. The method is applicable to flashlight photography, in which case the flash bulbs can be furnished with a blue varnish coating. Morris and Spencer³⁰ described a varnish which could be used for coating flash bulbs for this purpose and also a composition which could be used for making bags for covering the lamps.

PHOTOGRAPHS IN TOTAL DARKNESS

Infrared radiation is invisible. It is possible, therefore, to use it for taking photographs in total darkness, provided a film sensi-

tive to the infrared is used. This has been done on many occasions,^{19, 29, 137} usually for spectacular purposes, but it has also had serious applications.

Some of the earliest photographs to be made in what was considered total darkness were exposed by ultraviolet radiation. In fact, Fox Talbot in "The Pencil of Nature," in 1844 proposed that photographs be made in this manner. The first to execute this idea was Dodds³² in 1928. Attempts with it were described by Calzavara before the French Photographic Society on June 4, 1930. There are a number of drawbacks to the use of the ultraviolet for this purpose, however. For example, many objects, including the skin, teeth, and fingernails, fluoresce when irradiated by ultraviolet, so that, although the incident radiation itself might be invisible, it would render parts of the subject clearly distinguishable to the eye.

The infrared possesses the advantages of being available in high intensity from common light sources and of not inducing visible fluorescence. It is thus ideally adapted to photography in the dark. Two kinds of infrared source can be used. One of these includes the infrared radiators which do not emit any visible light. The other group comprises the normal incandescent

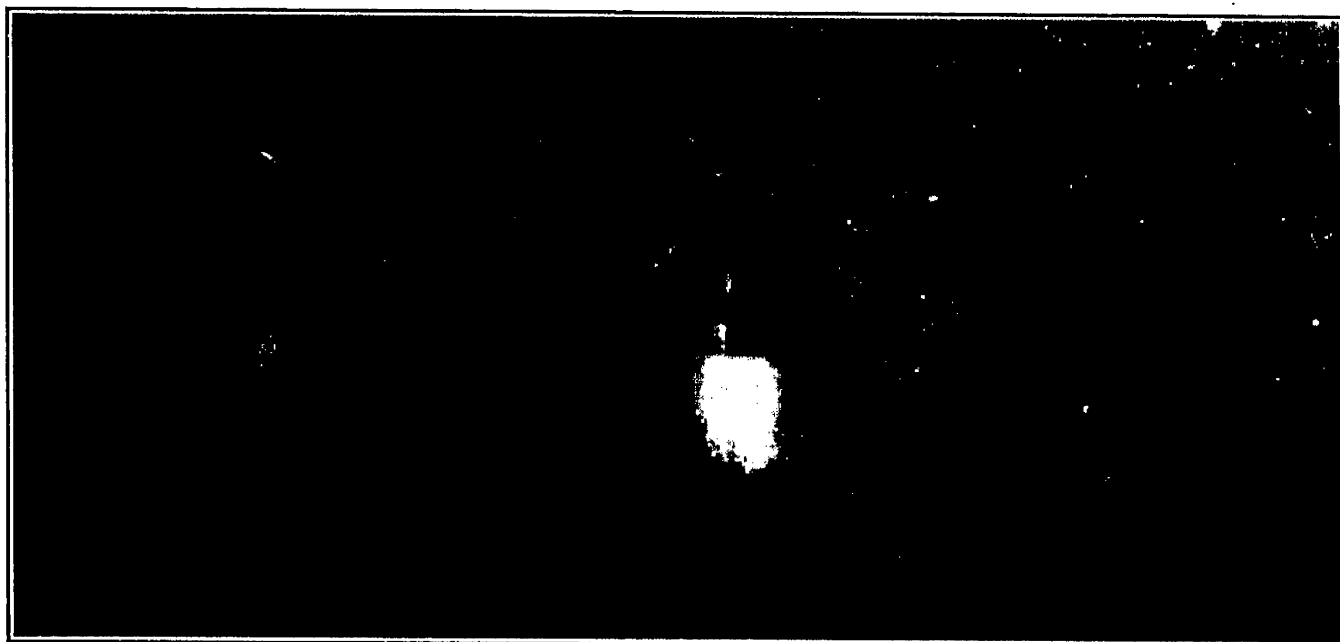


FIG. 65. The first photograph made in total darkness in 1930, using heat rays emitted by an underrun electric heater. Neocyanine plates were used.

(Courtesy H. D. Babcock)

lamps which can be screened by filters that absorb the visible light and transmit the infrared freely. Only the second group is of practical value.



FIG. 66. Portrait of a bust made in total darkness by the heat from two electric flatirons.

(Kodak Research Laboratories)

The first published photograph taken in total darkness appears to be that made by Babcock, of Mount Wilson Observatory, in 1930. It shows a bottle, a glass graduate, and a tin-can cover, which were photographed in a dark room on a plate sensitized with Neocyanine, using heat rays emitted by electric heaters underrun so as to be invisible (Figure 65). The plates were so slow, and the infrared intensity so low in the photographic region, that an exposure of 48 hours was necessary at $f/2$. In 1932 the Kodak Research Laboratories published a portrait of a plaster

bust made in a dark room with the radiation from two electric flatirons of 500 and 750 watts (Figure 66). The exposure was one hour at $f/4.5$ on the Eastman Infrared-Sensitive Plate Type I-R of that date. Since then many other photographs obtained by irradiating the subject with the rays from low-temperature sources have been published.

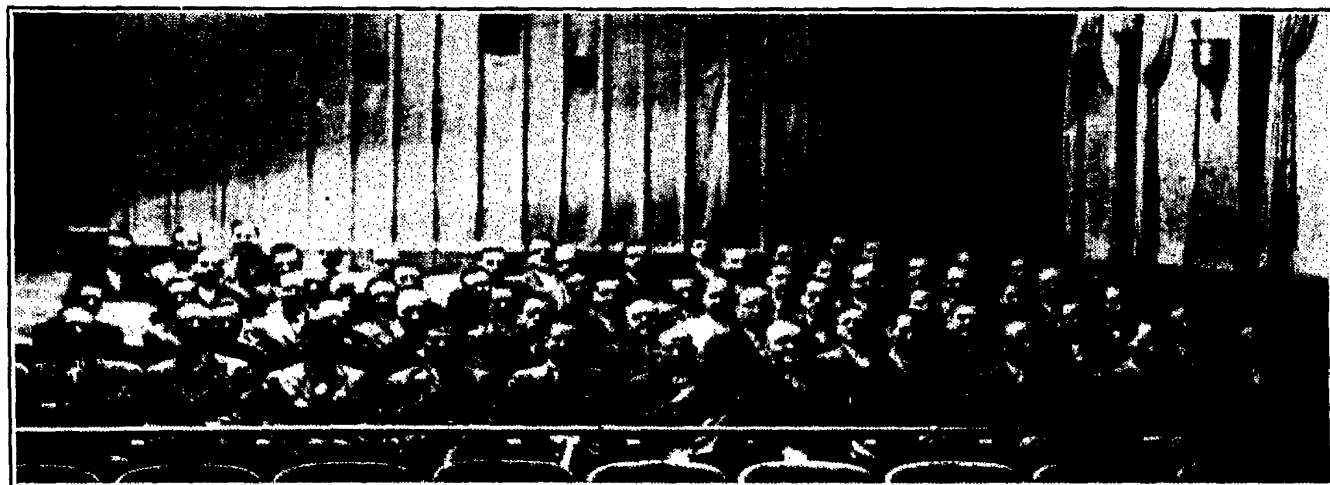


FIG. 67. Photograph of group made in total darkness in the auditorium of the Kodak Research Laboratories, October 7, 1931.

(Kodak Research Laboratories)

On October 7, 1931, a photograph of a large group was made in total darkness in the Kodak Research Laboratories. In this case, tungsten-filament lamps were used, screened with filters which allowed only the invisible infrared to pass. The technique employed may well serve as a model for others who wish to do the same sort of thing. The auditorium in the Laboratories is about 60 by 40 ft in size. The audience, consisting of about 60 people, was arranged in the middle of the room, and the camera was erected on the lecture bench at the front. At the side of the room towards the back was constructed a booth, closed at the sides, and containing fifteen 1,000-watt studio-type lamps in reflectors pointing towards the ceiling. The top of the booth was covered with sheets of Wratten no. 87 filter, which absorbs visible light, but transmits the infrared freely. The audience was thus "illuminated" indirectly by infrared reflected from the ceiling alone. With an Eastman Infrared-Sensitive Plate Type A (Mesocyanine) in the camera, a satisfactory negative was made

with an exposure of 1 second at $f/3.5$. A print from it is reproduced in Figure 67. With present-day infrared films the exposure would be considerably shorter.

Portraits can be made in total darkness by using normal studio lamps in their customary arrangement, if they are provided with infrared-transmitting filters in such a manner that no white light escapes from the lamphousing. Most of the infrared films and plates available at the present time are satisfactory for exposures of this kind, and there are several filters which can be used effectively for screening the lamps. The following conditions have proved adequate for making infrared portraits and will serve as a guide to the photographer: Two pairs of 500-watt (or Photoflood) lamps are used in reflectors covered with the Wratten no. 87 filter. With the units at about 6 ft from the subject, the exposure is about 1 second at $f/4.5$, with the Kodak Infrared Sheet Film. Naturally, it is not necessary to use a filter on the lens when making photographs of this type. Photoflash lamps may be substituted effectively for other lamps. Convenient lamphouses are provided by pyramid-type safelights lined with tinfoil. The infrared filters may be mounted between glass and used in the position normally occupied by the safelight glass. No white light leaks from such an arrangement.

The R2 Photoflood lamp has been used for infrared dark photography, either coated with an infrared lacquer or in a lamphouse covered with the Wratten no. 87 filter. Good negatives on Kodak Infrared Sheet Film have been obtained with one such lamp pointed directly at the subject 10 ft away, with an exposure of one-tenth second at $f/4.5$.

The chief problem in making photographs in the dark by using ordinary lamps lies in the proper selection of the filter to absorb all visible light and to transmit the infrared very freely. It is usually stated that the limit of visibility in the long wavelengths is at about 7,600 Å. Actually, it is not possible to name a definite threshold, since so much depends on the conditions of illumination and observation, and on the observer.⁸³ Measurements have been made at least up to 9,000 Å. For practical dark photography, however, it may be taken that a filter absorbing all light below about 7,600 Å will be satisfactory, provided the subject does not look directly into the lamps. The lamp filament

can readily be seen as a dark red image through a filter absorbing below 7,600 Å. If the subject is illuminated indirectly, the studio should appear quite dark. Suitable filters are the Wratten no. 87 and the Agfa no. 85.

INFRARED FLASH PHOTOGRAPHY

Flash bulbs provided with infrared filters can clearly be used to make flash pictures in the dark.^{149, 151} According to Isaacs,⁹⁸ such photographs were made about 1932, using clear flash bulbs in a box covered with an infrared filter. At the suggestion of A. Barrett, the Kodak Research Laboratories in England worked out a formula for an infrared-transmitting lacquer which could be applied to flash bulbs for candid photography and for photography in blackouts when regulations forbade the use of visible flashes. The formula was published in 1940 by Morris and Spencer.⁹⁶ It was suggested that, in addition to being used for lacquering flash bulbs, it could be made into bags which could be slipped over the bulbs. Soon after this, there arose a demand for infrared flash bulbs by the press photographers^{28, 110} and the Services in the United States, and their manufacture was started by the General Electric Company and the Wabash Photolamp Corporation. From the former they are obtainable as Mazda Synchro-Press lamps no. 22R and 5R, and from the latter as Blackout Superflash lamp no. 2 and the Blackout lamp no. 25.

A point of practical interest in blackout photography is the concentration of the infrared in the exposure. It is generally undesirable to use a reflector which concentrates the illumination. The reflector should preferably give well-diffused illumination. The actual exposure will depend on the nature and form of the reflector, so that it is not possible to give precise exposure tables. With the Mazda Synchro-Press no. 22R and the Blackout Superflash no. 2, Kodak Infrared Sheet film, and the shutter set at $\frac{1}{50}$ second or slower, good exposures should be obtained at 10 ft at an aperture of $f/5.6$.

If the subject is looking in the direction of the flash, he will perceive a deep red glow, since the lacquers on the bulbs are not entirely opaque to red. Infrared flash photographs which have been published include accidents and air-raid casualties, street scenes at night, audience-reaction photographs in motion-picture

theaters, and operations in photographic factories in which visible light would spoil the product being made.

The Ilford Company published an infrared photograph of a small photographic plate-coating machine in operation in the dark. In 1944 the Eastman Kodak Company published such a



FIG. 68. Study of audience reaction made by infrared from Kodatron lamps screened with Wratten no. 87 filters.

The effective exposure time was $1/10,000$ second, and the audience was unaware that it was being photographed while listening to a lecture.

(Kodak Research Laboratories)

photograph of a long row of operators spooling highly sensitive aerial film. The infrared flashes were strung up, and the camera was set up and its field and focus determined during the lunch period when the room was empty, and the film was stored in lighttight boxes. The photograph was made after the operators had resumed work and the room was in total darkness. Twelve Mazda 22R flash bulbs were used, one being suspended over each operator and machine in the camera's view, and two others for supplementary illumination. All flashes were fired simultaneously. Kodak Infrared Sheet Film was used, and the exposure was of the open flash type with a lens aperture of $f/16$.

The Kodatron type of gaseous-discharge flash lamp can be used for infrared flash photography provided it is covered with the Wratten no. 87 filter or its equivalent. Audience-reaction photographs have actually been made during the projection of motion pictures using three Kodatron lamps in a booth similar to that described on p. 320. The top of the booth was covered with sheets of Wratten no. 87 filter film between glass sheets, and the illumination was indirect, by reflection from the ceiling. One of the results is shown in Figure 68. It was made in 1945 on Kodak Infrared Sheet Film, with an aperture of $f/3.5$. The effective exposure time was $1/10,000$ of a second. The actual aperture used will naturally depend on the distance and size of the audience, the nature of the ceiling from which the infrared is reflected, and so on, and will have to be determined for each new set of conditions. Other invisible arrangements of lamps may suggest themselves, for instance, including them in the concealed cove lights or in exit or other signs in the theater. A deep red flash will be apparent if the lamps point directly at the audience without some form of disguise.

PHOTOGRAPHY OF HOT OBJECTS: PHOTOGRAPHIC THERMOMETRY

If an object reflecting or emitting light is photographed on a panchromatic film, the negative gives a record of the distribution of brightness over the surface. If suitable precautions are taken, the actual brightness at different points can be determined quantitatively. Similarly, if the infrared radiation emitted by a hot object is recorded on an infrared-sensitive film, some idea of the distribution of infrared emissivity, which is related to the temperature of the surface, may be obtained. In this way, we have the subject of photographic thermometry, analogous to photographic photometry.

Shortly after the introduction of infrared emulsions of relatively high sensitivity, photographs were made of electric flat-irons, soldering irons, hot plates, and such, in total darkness. In many instances the location of the heating elements could be identified from the lightest part of the photograph.

Infrared photography can be used for studying the distribution of temperature of surfaces from about 250°C to approach-

ing 500° C. For temperatures below 250° C the exposure times are far too long, whereas above 450 to 500° C visible radiation is emitted and panchromatic films can be used. If a heater such as a flatiron is operated under rated conditions in a dark room, it is usually just visible to an adapted eye. Objects at a temperature of 600° C are clearly visible in a lighted room. At 500° C they can be seen readily in a dark room, whereas at about 420° C they are just visible after the eye has been adapted for a long time in the dark. Below this temperature objects can be considered to be invisible. Abney once stated that it might be possible to photograph a kettle of boiling water by its own radiation. This actually appears to be quite out of the question, however.

In the photography of hot objects for the determination of the distribution of surface temperature (or emissivity), the object should be photographed in the normal manner in the dark, on a fast infrared film. It is usually preferable to use film having sensitivity in the normal region of fast infrared materials, that is, with a peak about 8,000 to 8,500 Å. Films or plates sensitive further in the infrared are usually not satisfactory, since their sensitivity is too low. High-aperture lenses should be used. The surface of the hot object should preferably be dark, not polished bright.

The temperature range which can be covered properly by one exposure on one sheet of film does not exceed about 150° C. Its limits are determined by the latitude of the film. The actual position of the temperature range on the total temperature scale will naturally determine the exposure required. It will be longer, the lower the temperature.

In order to be able to interpret infrared exposures of hot objects quantitatively, it is necessary to employ the precautions which are used in photographic photometry. The most important of these is to include on the negative a series of exposures to a standard hot body operated at known temperatures. The densities in the negative of the hot object can then be compared with those of the calibrating exposures and the temperature ascertained. A convenient way of applying the standard exposure series suggested by E. W. H. Selwyn consists in photographing a triangular piece of metal foil through which an electric current

is passed. Such a foil will vary in temperature according to its width and is calibrated with a pyrometer or thermocouple. Alternatively, a group of electrically heated objects of known temperatures may be photographed, or a metal bar, heated at one end as the well-known bars for determining melting points, and having a temperature gradient throughout its length. These must naturally be calibrated for temperature by a thermocouple or other means.

A curve relating temperature to exposure required to produce a particular density at a particular aperture can be determined for the infrared film used and will serve as a future guide for exposure when the approximate temperature range is known. With Kodak Aerographic Infrared Film (which has about twice the speed of the more readily available Kodak Infrared Sheet Film), exposure of two hours at $f/4.5$, and development for 8 minutes in Kodak D-19 at 68°F , a temperature range of from about 335° to 450°C can be recorded on the greater part of the density range of the film, the toe and shoulder regions being ignored. Over this range the relationship between temperature and log relative exposure is practically linear.

Quantitative aspects of the subject have been considered by Hase,⁵⁵ Hencky and Neubert,⁵⁶⁻⁶⁰ Plotnikow,¹¹⁵ and Fischer.⁴³ Photographic thermometry has been applied to study of electrical resistances and heating appliances, heat losses in furnaces due to weaknesses in insulation, temperature of furnace walls, superheated steam lines, hot metal ingots, cylinder head and exhaust manifolds of internal combustion engines, welding operations, and radio tubes.¹⁵⁰

Some work has been done on the production of heat-sensitive papers which might be applicable to measuring surface temperatures over a lower range than that which can be recorded photographically. The quantitative aspects have not been worked out at present, however.

APPLICATIONS IN TECHNOLOGY

Many uses of infrared photography in technological fields have been described in the preceding section of this chapter dealing with the photography of hot objects and in other chapters concerned with special applications. There are a few other uses

which have been tried with some measure of success, and they may well be discussed here.

In studying the interior of certain types of furnaces while they are in operation, considerable difficulty may be encountered as a result of haze due to fine dust. The interior walls of such furnaces may often be photographed satisfactorily if infrared is used, since it penetrates fine haze better than does visible light. In a gas-fired reverberatory furnace in which it was desired to photograph the burners from the other end of the furnace, some improvement resulted from incorporating some potassium salts in the gas. When the gas burned the characteristic spectral lines of potassium in the near infrared were obtained and could be photographed on an infrared plate, used in conjunction with a filter absorbing visible light.

A special study of the photography of the interiors of furnaces during operation has been made by Markson⁸⁴ and Dargan.⁸⁵ Infrared film is preferred for the black-and-white photography, especially as it is possible to make the exposures by the longer wavelengths alone and so reduce the haze effect which is due to the shorter wavelengths present in the flame itself. By using infrared film it is possible to expose for those objects which are richer in the heat wavelengths, such as the tubes, without overexposing the brightest parts such as the flame particles, slag, and refractories. The resulting photographs show much detail, and Markson has published some striking examples.

Infrared photography may also be of help in the study of arcs, especially in the formation of silicon carbide, where the haze due to volatilization tends to spoil pictures made on panchromatic film. Plotnikow,¹¹⁵ Bonhoeffer,²⁰ and Eggert⁴¹ used it to study combustion in the Bunsen flame.

Infrared photography by transillumination has also been used for studying defects in structure and in welds in synthetic plastic sheets.¹³³ Bubbles and weld characteristics are revealed in sheets up to 5.5 mm thick by using plates sensitive about 10,500 Å and a point source.

Tiffin¹⁴² considers that the infrared is to be preferred to visible light in the photography of etched specimens of fusion welds. Among the advantages claimed are a greater contrast among the weld metal, the zone of fusion, and the heat-affected zone; de-

fects within the structure of the weld and the parent plate are more clearly outlined and emphasized.

Carbon is opaque to the infrared. Based on this fact, infrared photographs have been used to show the presence of carbonaceous matter in lubricating oils which have been used in internal-combustion engines.⁷⁶ By their means it is possible to judge the efficiency of addition agents or chemical treatment designed to prevent the deposit of carbon.

Infrared photography has been used successfully by Taffs, metallurgical microscopist to the International Tin Research and Development Council, in the study of porosity in tin plate. The author is indebted to Mr. Taffs for the description of the technique employed and for the illustrations in Figures 69 and 70. The usual procedure is to introduce, as nearly as possible, conditions for vertical illumination. This is done in the following manner: A white card *A* (see Figure 69) is pinned to the front of the camera *B* and the specimen *E* is fixed to the easel *C*. The lens is swung as far as possible to the same side as the white card.

The card *A* is evenly illuminated by a focusing spotlight *D*. The tin plate *E* reflects the light which is incident on it from the white card. The result is that the specimen appears light, and any irregularities (which have a minimum depth of approximately 0.0002 in.) or spots on it scatter the light and appear dark, and can be photographed. The procedure is very useful when one

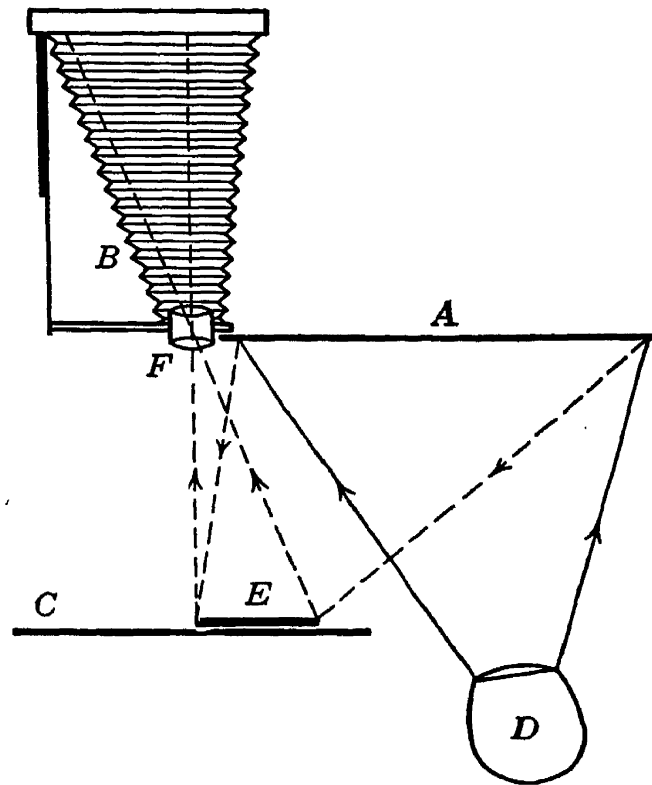


FIG. 69. Diagram of arrangement for photographing tin plate to study porosity.

(Courtesy H. J. Taffs, FRMS, FRPS, Metallurgical Microscopist to the International Tin Research and Development Council)

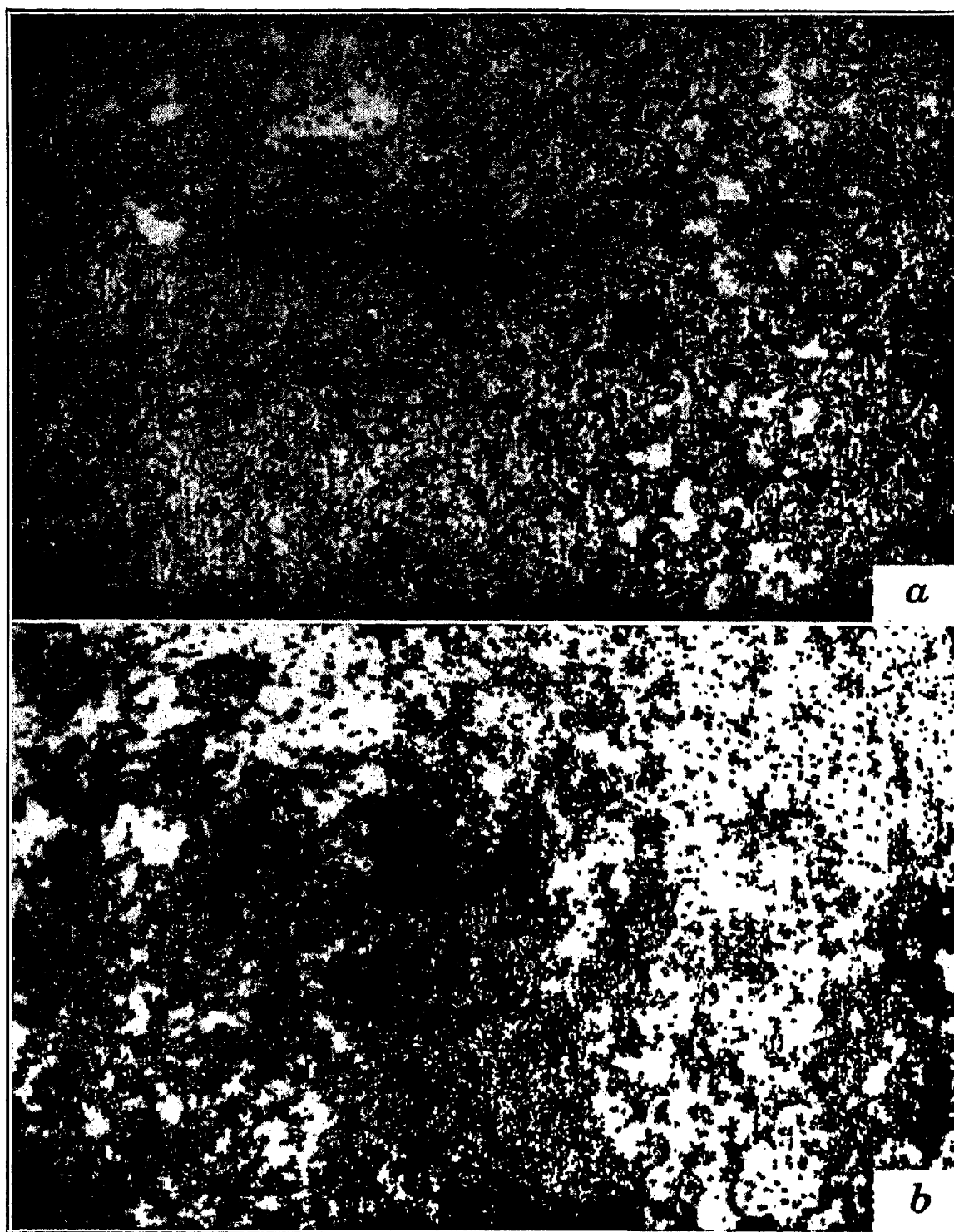


FIG. 70. Photographs showing porosity of tin plate after it has rusted in hot distilled water.

Photograph *a* was made on an orthochromatic plate and *b* on an infrared plate. The film of rust which tends to mask the pore sites on *a* is overcome in *b*.

(Courtesy H. J. Taffs)

is recording the porosity of tin plate after it has rusted in hot distilled water, a method of testing now much in use in which the rust spots or pores appear as dark areas on a light ground. When a number of pores in the specimen lie close together, the rust tends to form a film over the surface of the tin surrounding the pores. When the sample is photographed with ordinary plates, the film tends to mask the actual pore sites. This difficulty is overcome by the use of infrared-sensitive plates, which differentiate between the pores and the film. A pair of photographs showing the improvement obtained by the use of the infrared appear in Figure 70. In the illustration, A is a photograph made on an orthochromatic process plate, while B was made on an infrared plate.

In electrophoretic and ultracentrifugal analysis, difficulty is sometimes encountered in examining protein solutions containing dyes or bacterial pigments because of their opacity to visible light. Many of these coloring materials are transparent in the near infrared, and the difficulty can therefore be overcome by infrared photography.¹⁴³

In recent years there has been a rapid growth in the application of infrared drying in industrial processes, such as lacquers, enamels and other finishes, printers' inks, ceramic articles, glazes and colors. These processes are of little concern to the photographer, except insofar as infrared drying has been applied with success to film processing machines.

SPECTROGRAPHIC AND ASTRONOMICAL PHOTOGRAPHY

Among the many applications of infrared photography in the fields of scientific investigation, the most important are in spectrography and astronomy. In spectrography, the infrared is used in the detection of the elements and in the elucidation of atomic and molecular structure. There are three types of molecular spectra, which are known as electronic, vibrational, and rotational. They are derived from the motion of the electrons, from the mutual vibrations of the nuclei which constitute the molecule, and from the rotation of the molecule as a whole. The electronic spectra are confined almost entirely to the ultraviolet and visible, the vibrational to the region lying roughly between 10,000 and

300,000 Å ($1\ \mu$ and $30\ \mu$), and the rotational from about 150,000 to 5,000,000 Å ($15\ \mu$ and $500\ \mu$). All of these regions are used in the determination of molecular constants, structure, and analysis, although the photographic method is clearly applicable only to a relatively limited portion. The long-wavelength regions are investigated by thermoelectric elements, particularly the vacuum thermocouple, the radiometer, the thermopile, and the bolometer.^{14, 15, 47, 118, 119, 120, 138, 141}

The photographic spectrum includes the visible and infrared to just beyond 13,000 Å. That this region is very important spectrographically was first made clear in connection with molecular structure by the work of Mecke.⁸⁷ In 1929 he discovered certain bands of acetylene in the region of 8,000 Å which enabled the moment of inertia of the molecule to be determined accurately. The method has been applied to other molecules such as hydrochloric acid, hydrocyanic acid, water, ammonia, ethane, and methane, although with some of them, the analysis and interpretation of the bands are quite complicated.

The photographic method has a number of advantages over the purely physical: the technique is very simple; the exposures can be integrated over a long period of time, whereas this is not possible with the thermoelectric detectors; a high degree of resolution is possible in the spectrographs, so permitting the analysis of fine structure in the bands.

It is not the purpose of this book to go into details of the sources of infrared, the arrangement and operation of the spectrographs, and the analysis of the spectra. There are a number of excellent treatises on these subjects mentioned in the bibliography, and, in addition, the physical journals contain innumerable articles which should be consulted by the interested worker. It must suffice here to mention a few of the outstanding results of spectrography which were made possible by the introduction of special infrared plates. The majority of the applications of infrared in the astronomical field are spectrographic, and much has been learned of the constitution, temperature, and atmospheres of the sun, stars, and planets. Mention is made of a few of these and of some other astronomical applications of infrared photography not involving the spectra.

One of the most remarkable achievements in infrared spectrography was due to Abney.¹ In 1881 he described the results of experiments, lasting over five years, on the photography of the infrared spectrum of the sun and presented a map of the solar spectrum between wavelengths 7,600 and 10,750 Å. The photographs were made on silver bromide-collodion plates which were blue by transmitted light and so absorbed the red and also the infrared rays. He argued perfectly correctly that, if he could prepare an emulsion which absorbed red light, it should be sensitive to the red. In practice, his theoretical reasoning was given ample support. Abney's method, however, was not used for many applications because it was exceedingly difficult to prepare plates by its means. In fact, Ritz¹²³ is the only other investigator who was able to accomplish much with it.

Prior to 1931 a number of other photographs of the infrared spectrum were made, using the special methods described in Chapter VI, and emulsions sensitized with dyes.⁸⁸⁻⁹⁰ They included the following results: Higgs in 1891 photographed the near-infrared solar spectrum; Lehmann in 1900 recorded lines out to 9,000 Å; Meggers and Merrill, and McLennan photographed to about 10,000 Å, using Dicyanine; Kryptocyanine, discovered in 1919, permitted photographs of the near infrared to be made very readily to about 8,000 Å. With the introduction of Neocyanine in 1925 it was possible to extend the spectrum still further with relative ease, and in 1930, using Neocyanine plates, Babcock photographed the solar spectrum to 11,634 Å.

The year 1932 saw the introduction of the new types of infrared sensitizers, and a new era in infrared spectrography set in. Meggers and Kiess⁹³ published the results of photographs of the spectra of 50 elements in the region from 8,000 to 11,000 Å. In 1933 Meggers⁹¹ recorded the emission spectra of the alkalis and alkaline earths between 8,500 and 11,800 Å and showed a large number of lines and bands. Kiess⁷⁴ in 1933 discovered 130 new lines in the arc spectrum of silicon between 6,125 and 11,290 Å. The year 1935 showed a further advance in which Meggers⁹² discovered many new lines in the spectra of the noble gases and photographed large numbers of lines in the region 10,500 to 13,000 Å; in the same year Kiess⁷⁵ found some 30 new lines in the arc spectrum of copper out to 12,000 Å.

In Germany Herzberg^{39, 40} made a special study of infrared spectra. Among the important photographs which he has obtained may be mentioned those showing the absorption bands of acetylene at 10,300 and 10,900 Å, of hydrochloric acid at 12,000 Å, ammonia bands at 10,400 Å, and lines in the solar spectrum to 13,260 Å. Badger and Bonner of Mount Wilson Observatory photographed the spectrum of ethylene to 11,130 Å. The mercury line at 11,287 Å has been photographed frequently in recent years.

The furthest extension of the photographed spectrum was made by Babcock at Mount Wilson Observatory in 1935, when he recorded the lines of the solar spectrum out to 13,500 Å (see Figure 71). Following this, Babcock, Moore, and Hoge¹⁰ established the scale of wavelengths in the spectrum of the sun out to 10,603 Å and a list of tentative standards from 10,600 to 12,103 Å. In 1935 Dingle³⁰ established standard wavelengths in the spectrum of the iron arc from 8,838 to 10,219 Å.

Infrared spectrography has been applied with striking success to the study of the spectra of many stars, by using spectrographs of very high dispersion. The Balmer and Paschen series of hydrogen, the infrared lines of ionized calcium, the A and B bands of oxygen in the solar spectrum and in the spectra of sunlight reflected from Mars, the cyanogen absorption bands in *N*-type spectra, the spectra of the planets and the rings of Saturn, the spectra of the long-period variable stars, and numerous other spectra of intense interest to the astronomer have been photographed since the introduction of the present types of infrared plate.^{33, 39, 40, 97}

Perhaps the observations of greatest popular interest concern the atmospheres of the planets. The presence of carbon dioxide has been shown in the atmosphere of Venus (see Figure 72); of ammonia in the atmospheres of Jupiter and Saturn; and of methane in the atmospheres of Jupiter, Saturn, Uranus, and Neptune.^{4, 124, 125, 129} Study of the B band of oxygen at the end of the visible in the spectrum of Mars³ indicated that the amount of oxygen in the atmosphere of the planet must be extremely small, certainly less than 1 per cent, and probably less than 0.1 per cent of that present in the earth's atmosphere over equal areas of surface.

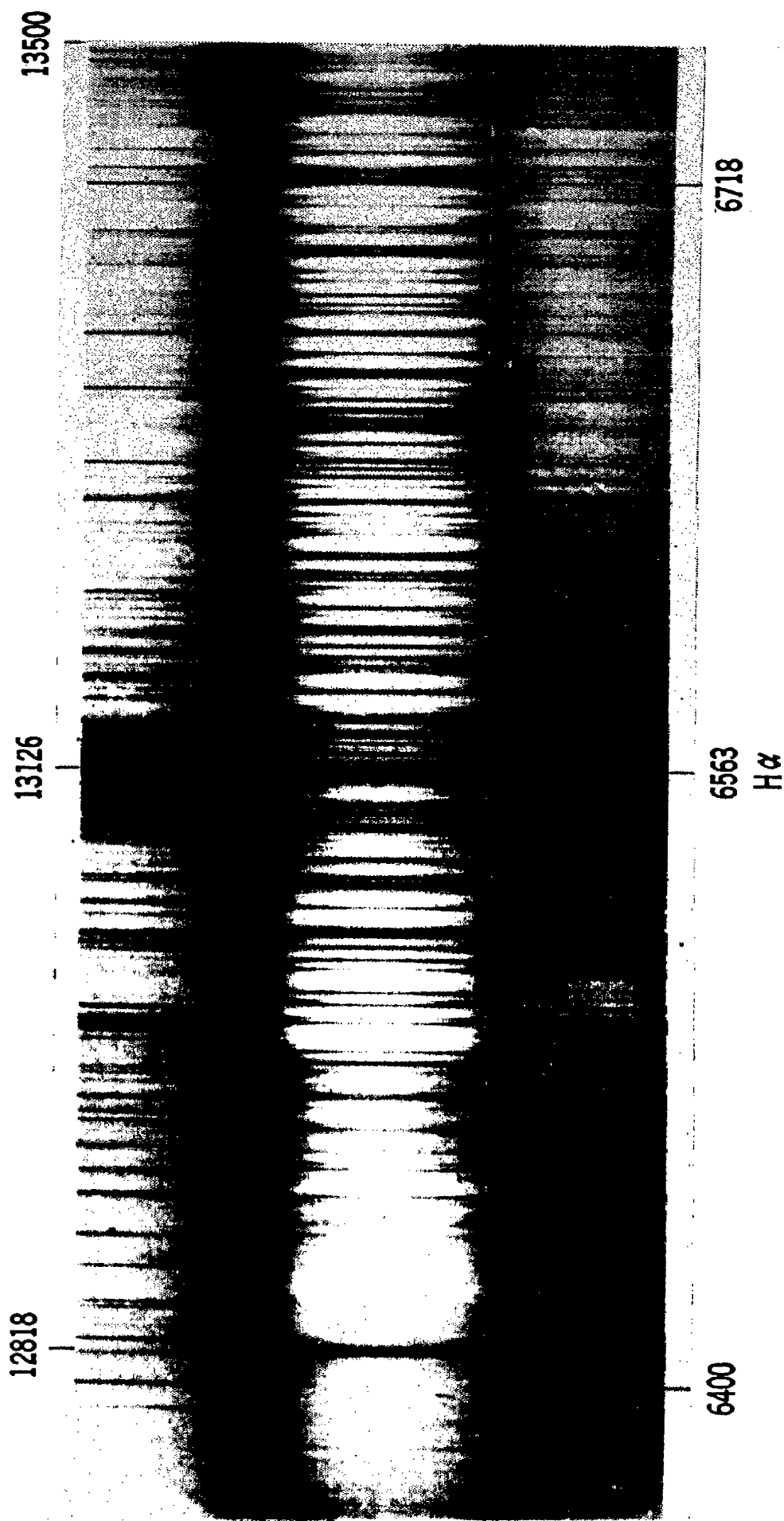


FIG. 71. Infrared photograph of the solar spectrum to 13,500 Å.

The central strip is the first-order spectrum from 12,730 to 13,500 Å. The comparison spectra on both sides are second-order spectra from 6,365 to 6,750 Å.

(Courtesy H. D. Babcock and Mount Wilson Observatory, Carnegie Institution of Washington)

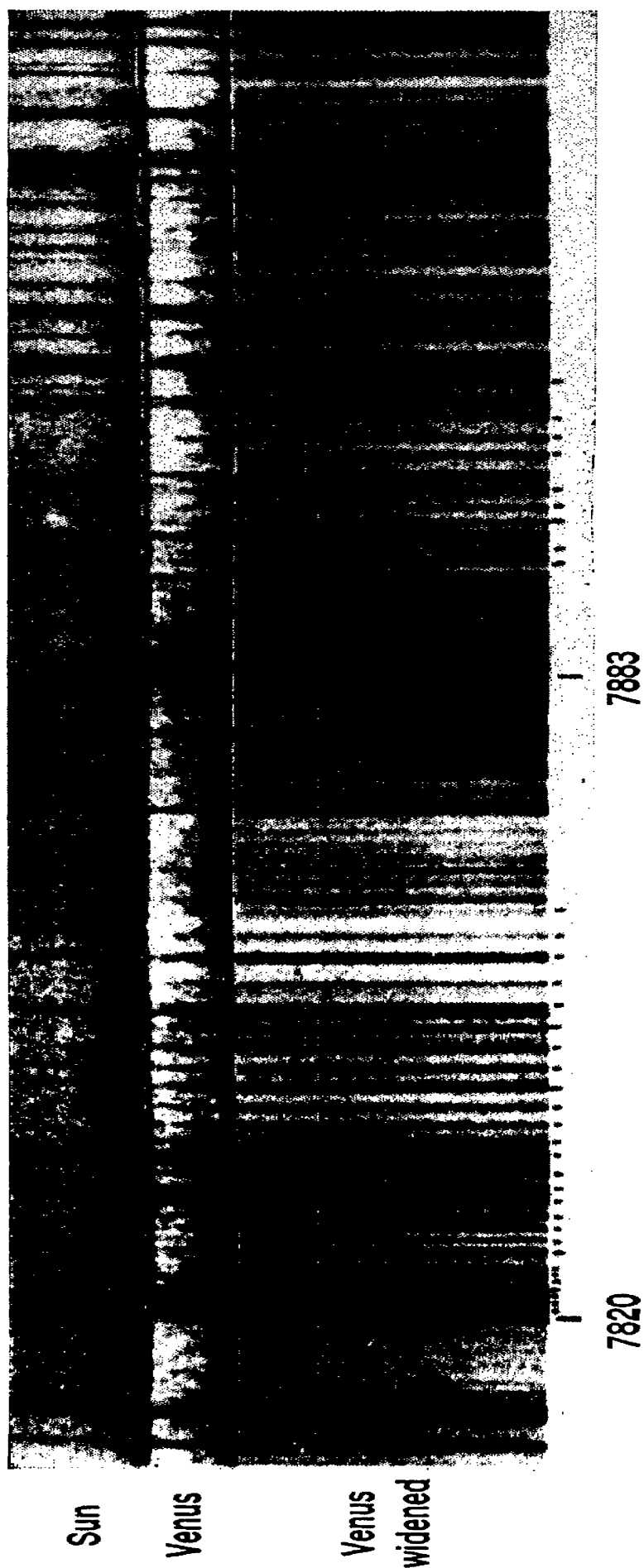


FIG. 72. Infrared photograph of band showing the presence of carbon dioxide in the spectrum of Venus. The top spectrum is that of the sun, by which the planet is illuminated; the middle spectrum is that of Venus; the bottom spectrum is that of Venus widened. The bands characteristic of carbon dioxide are dotted. They are present in the spectrum of Venus and absent from that of the sun.

(Courtesy W. S. Adams, T. Dunham, Jr., and Mount Wilson Observatory, Carnegie Institution of Washington)

Prior to these spectrographic observations, the planets had been photographed in the normal manner through the telescope, in order that their infrared characteristics might be compared with those observed by ultraviolet and visible radiation. After some pioneer infrared photographs of the moon which he had made in 1912, Wood made some photographs of the planets Jupiter and Saturn by ultraviolet, visible light, and infrared. A special study of Mars was made in this manner by Wright in 1924.¹⁵⁷ Kryptocyanine-sensitized plates employed showed the permanent surface markings of the planet with much higher contrast than was obtained with other plates. By analogy with the observations on the penetration of atmospheric haze by the infrared, it was deduced that Mars was surrounded with an atmosphere of appreciable absorbing and light-scattering power.

Swings¹⁴⁰ made some suggestions for infrared observations of the solar corona. Although his wavelengths are beyond the photographic range, he does suggest that Czerny's evaporographic method should be tested to show coronal lines. In fact Swings appears to be very interested in this method for astronomical photography (see p. 115).

Astronomers have successfully used the extreme red and infrared to photograph stars which are invisible through the luminous haze of nebulae. A pair of photographs of the Orion Nebula was made by Dr. Trumpler, one by violet and blue light, and the other by the extreme red. The nebula largely disappeared on the infrared plate, revealing stars which were invisible to the eye, and not seen on the blue-violet plate. Another more recent pair of photographs, also made by blue-violet (A) and infrared (B) by Dr. Struve, is shown in Figure 73. The nebula has completely disappeared on the infrared plate, but there is a strong group of "infrared" stars where the nebula is located. The absence of the nebula is due to the fact that the hydrogen Paschen emissions are much weaker than the Balmer emissions, which are shown in the blue-violet photograph. The exposures of the two photographs were adjusted so that the background of the sky between the stars had approximately the same density. From an examination of the background, and of stars of different colors, it is found that the sky is relatively much stronger

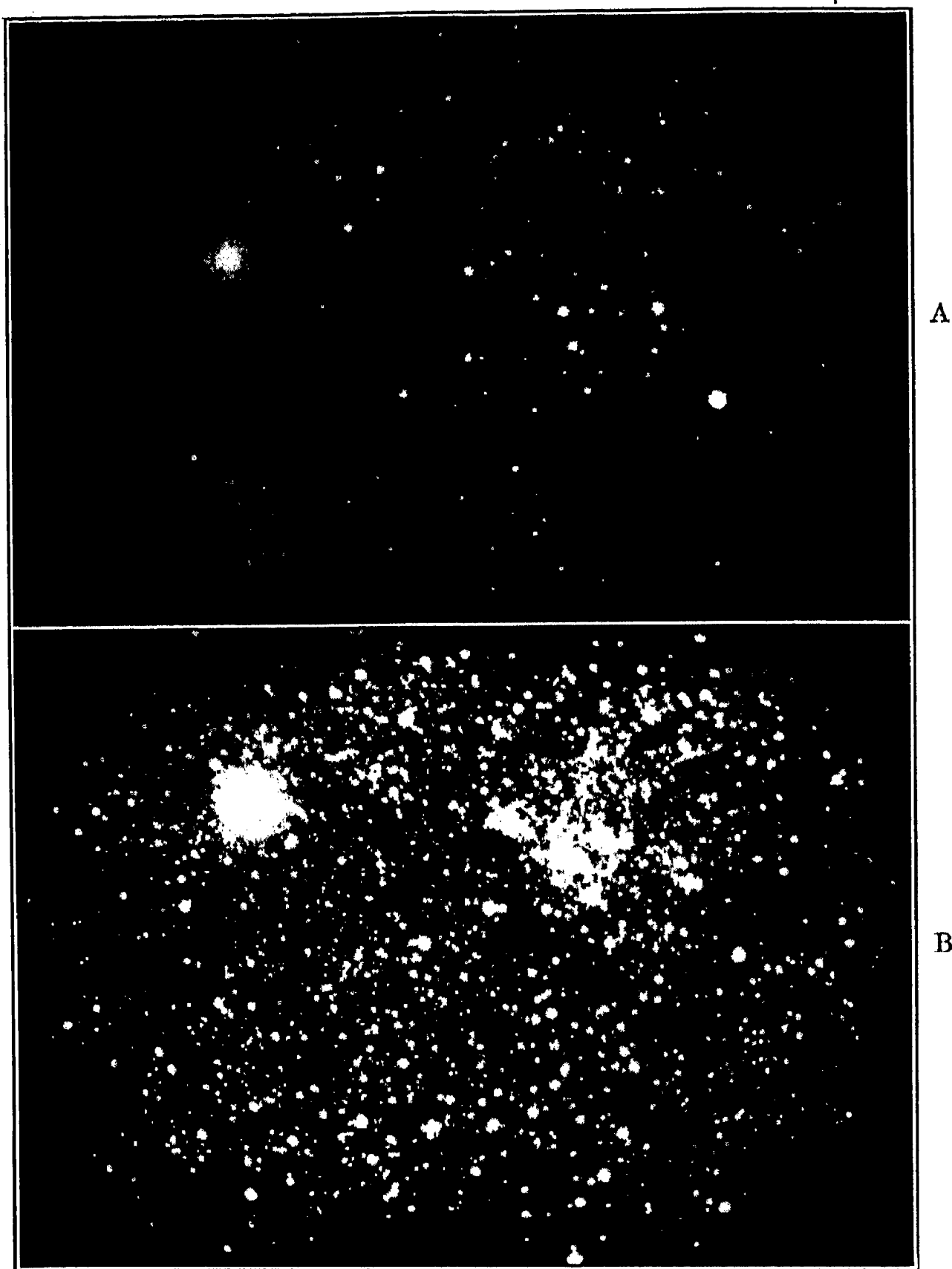


FIG. 73. North American Nebula. A, by blue-violet light; B, by infrared.
(Made by Otto Struve of Yerkes Observatory)

at a wavelength of 8,500 Å than in the blue and violet parts of the spectrum. If the human eye were sensitive to infrared of this wavelength, the night sky would appear as a pale glowing surface upon which the stars were relatively dim points. Dr. Baade at Mount Wilson Observatory used the Eastman Type 1-N spectroscopic plate to show the inner mass of the Crab Nebula which emits a continuous spectrum. On a far-red-sensitive plate this is largely masked by a filamentary network which has strong emission lines in the red. Many so-called "infrared stars" have been found on astronomical photographs made exclusively by infrared, but are invisible on photographs made by blue-violet light. A typical discovery photograph of infrared stars, made by Dr. Hetzler⁶³ of Yerkes Observatory, is shown in Figure 74, which represents the method very well. Several bright ordinary stars shown in the two photographs, made, respectively, by blue-violet and infrared, are marked by straight lines. The infrared stars are surrounded by circles and squares, and some of them are completely invisible on the blue-sensitive plate. At the beginning of 1938 Dr. Struve reported the discovery of a new large star, named Epsilon Aurigae, entirely as a result of the application of infrared photography.

In a consideration of the possibilities of astronomical spectroscopy in the infrared, Swings¹³⁹ surveyed the known methods and listed the following data probably to be obtained by observatories in the photographic infrared: (a) many forbidden lines, especially those due to metals, should appear in peculiar bright-line stars, novae, and possibly nebulae; those which correspond to low excitation may reach considerable intensity; (b) lines of various light elements, such as O1 and N1, are strong in the infrared and should provide valuable information especially concerning stars with extended atmospheres; certain infrared lines of C11, C111, and other elements would permit a more thorough discussion of the selectivities present in Of stars, P Cygni, and Be stars. Interesting results will also be obtained from the Me stars; (c) new molecules, mainly polyatomic, should be found in comets, and possibly also in planets and satellites; (d) new diatomic molecules may be found in late-type stars and possibly even triatomic molecules.

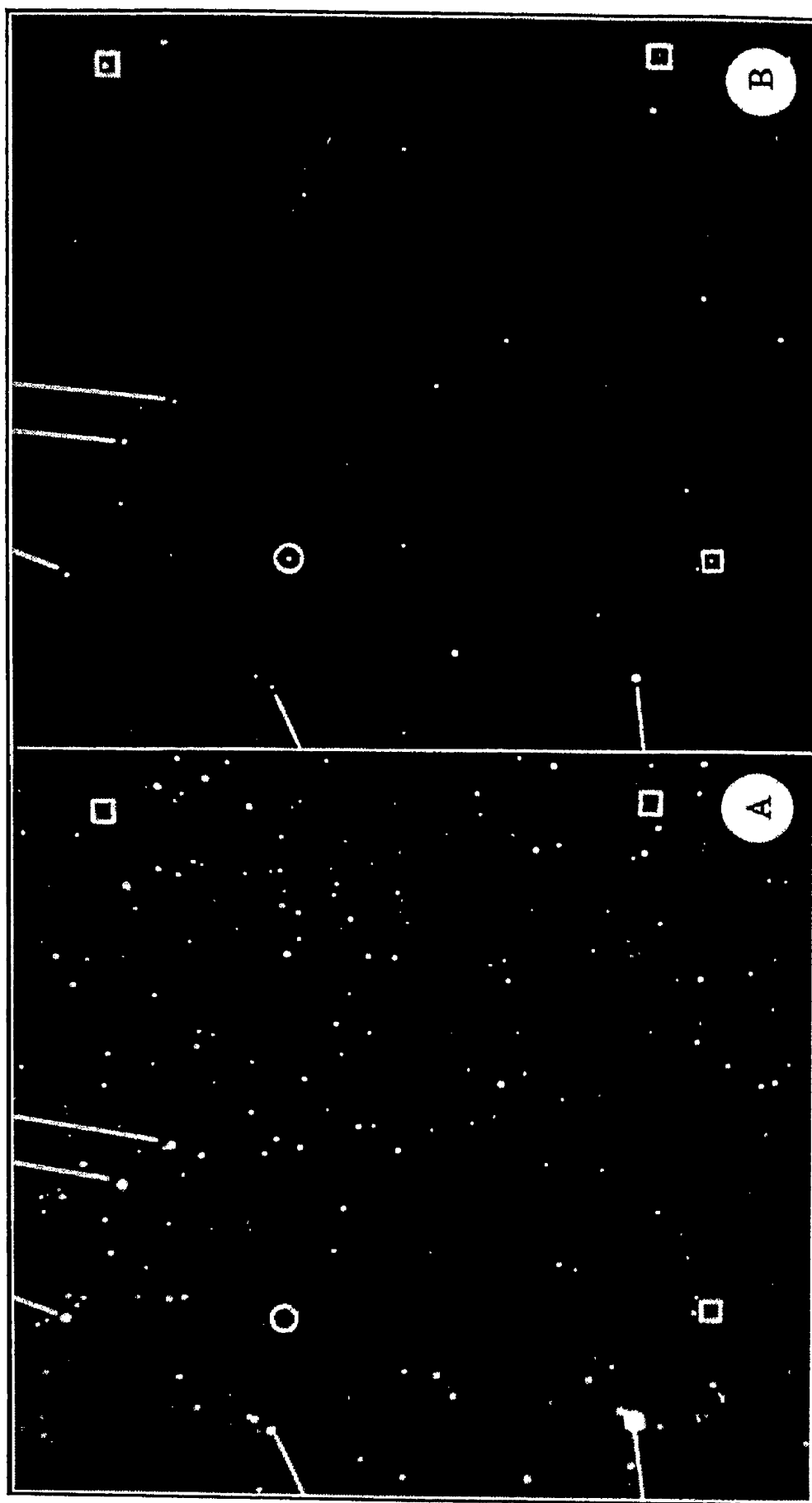


FIG. 74. Discovery photograph of infrared stars.

Photograph A was made by blue-violet light on an Eastman Hyperpress plate without filter, while B was made on an Eastman Spectroscopic Plate, Type 1-P, hypersensitized with ammonia, with the Wratten filter no. S7. Several bright ordinary stars shown in both photographs are marked by straight lines. The infrared stars are surrounded by circles and squares, and some are completely invisible in A. Both photographs were made with the 24-in. reflector of the Yerkes Observatory. (*Courtesy C. W. Hetzler*)

INFRARED PHOTOGRAPHY OF THE NORTHERN LIGHTS

Successful infrared photographs were made of the Northern Lights and their spectra by Bauer,¹⁶ Vegard,¹⁴⁴⁻¹⁴⁸ and others^{134, 135} in 1931 and 1932. The intensity is so low that even with the most sensitive plates and lenses of the highest aperture very long exposure times are necessary. It is only possible to photograph the very bright stationary lights. Bauer photographed stationary arcs with an exposure of 2 minutes on a hypersensitized Agfa Infra-red plate 810, through a Wratten no. 88 filter, and a Zeiss red filter, with an Astro R. K. objective at $f/1.25$. This appears to have been the first photograph to show that there is an infrared component in the Northern Lights. Its spectrum was first recorded by Vegard, who found two bands, a strong one at 7,883 Å and a weak one at 8,095 Å. Further infrared spectrograms by Vegard and Harang¹⁴⁸ showed eight infrared bands extending out to 8,150 Å. Surveys by Vegard,¹⁴⁴⁻¹⁴⁸ Hewson,⁶⁴ and Störmer^{134, 135} should be consulted by the interested reader.

In 1945 Stebbins, Whitford, and Swings¹³² reported the presence of strong infrared radiation at about 10,440 Å in the radiation from the night sky, and due to molecular nitrogen.

ETHNOLOGICAL STUDIES

In 1932 Bloch¹⁹ made a series of photographs of Negroes by visible and infrared radiation in which a very marked difference in appearance was observed. It was concluded that the appearance of the infrared photographs of the Negroes indicated Mongoloid characteristics not obvious in the normal photographs. A study of a large series of such photographs made by Seligman,¹²⁸ however, led to the conclusion that they are not of anthropological interest. Mongolian characteristics are definitely not observable, although the photographs show a lightening of the skin and other characteristics of infrared portraits. Quite a number of infrared portraits of Negroes have been published, and all show the skin as light.

PSYCHICAL RESEARCH

Photography has been used to some extent in the investigation of the mysterious and in the field of psychical research. It is

well known, of course, that so-called "spirit" photographs have been made, purporting to carry images of the departed. Further, attempts have been made to photograph the so-called "human aura," using as a filter a solution of the sensitizing dye, Dicyanine; these naturally are doomed to failure since the "aura" is actually a physiological optical effect due to the chromatic aberrations of the eye, and the dichroic nature of the transmission spectrum of dicyanine. The photographic camera has also been used to ascertain whether certain phenomena alleged to occur naturally are actually fraudulent. In this class fall the pictures which have been made of the Indian rope trick, in which connection it is stated that the evidence points to the fact that the thing has never actually been done.

In spiritualist séances it is customary for the medium to demand that the proceedings be carried out in a dim light. Although it is not the intention to imply that fraudulent practices occur at these meetings, it is clear that the condition of low illumination may be conducive to fraud. In a broadcast address delivered in London early in 1934, Professor C. D. Broad suggested that infrared photography might provide a means of obtaining a record of such séances. This has actually been done, to the writer's knowledge, in England, France, and the United States. Although his advice has frequently been asked concerning the technique to be employed, he has never been acquainted with the results of such investigations. The reason for this is probably that he does not move in psychic circles, and the results of these experiments rarely are made public. To photograph séances by ultraviolet radiation also has been attempted. It would not be expected, however, that such a source would be satisfactory, for a considerable intensity of ultraviolet would be required, and various objects, including the skin and teeth of humans, fluoresce strongly in the ultraviolet.

A method of infrared photography has been proposed by Rayleigh^{121, 122} which may be of some value in studying the occurrences at séances. He suggests that a field lens be illuminated by a light source screened by an infrared-transmitting filter, and that it produce an image of the source on the camera lens which is so focused as to give a picture of the aperture of the field lens. If any object moves across the field lens its silhouette may be

photographed with a very short exposure. By a photoelectric device, it is possible to operate the shutter of the camera automatically as soon as an object obscures part of the field lens.

Isaacs⁴⁸ used clear flash bulbs in a box covered with an infrared filter for photographing psychic phenomena. A similar arrangement was used by Fodor⁴⁴ in a series of exposures, the results of which he claimed showed the séances to be deceptive. Evans⁴² used infrared flash bulbs in photographing meetings in which he was the medium, and published pictures showing alleged levitations and the formation of ectoplasm prior to a complete materialization.

PHOTOGRAPHY OF DIAMONDS

Improvement in the photography of diamonds is claimed by Waters¹⁵² if the infrared is used. As a source he selects a 1,000-watt lamp screened with the Wratten no. 87 filter, and illuminates the subject as closely as possible in line with the camera. The jewelry is best arranged on black velvet as a background with bits of plasticine to hold it in proper position if necessary. With the old Eastman Infra-red plate Type I-R the lamp at a distance of 3 ft, and a stop of $f/22$ to secure sufficient depth, the exposure was about one hour. It would probably be about one tenth of this with the present types of film. Good negatives were also obtained with the same exposure, using the infrared from four flatirons.

EXAMINATION OF PEARLS

Artificial pearls are made by placing a nucleus of mother-of-pearl in the oyster shell. In order to accelerate the rate of growth of the pearl, these nuclei are generally much larger than those which give rise to natural pearls. The pearl material and mother-of-pearl consist of lamellae of the form of calcium carbonate known as aragonite. If the pearl is transilluminated in a direction parallel to the planes of the lamellae, it is very transparent. When pearls are threaded on a string, no attention is paid to this orientation, so that, if a string of pearls is laid on a photographic plate and a shadow photograph is made by transillumination, the majority of the pearls are so arranged that the incident light is at an angle to the plane of the lamellae. Under these conditions the pearls show a marked absorption of the radiation. With

artificial pearls, in which the nuclei are large, the photograph generally shows a large dark area in the pearl. Transillumination by ultraviolet was used by Leroux and his coworkers^{81, 82} to distinguish between natural and artificial pearls in this manner. Soft X rays have also been used.

Weber and Savic¹⁵³ made similar studies using red and infrared radiation. They employed artificial pearls having large nuclei covered with a relatively thin layer of pearl substance, so that their optical properties were determined largely by the nuclei. They found that the artificial pearls could, in general, be distinguished from natural pearls in infrared photographs made by transillumination. They showed large dark areas as compared with the higher transparency of the natural pearls. The method of shadow photography of Plotnikow was used, and, in order to ensure success, great care was necessary to obtain correct exposure.

SHADOW PHOTOGRAPHY AND LONGITUDINAL SCATTERING

Since the early days of photography it has been common practice to make photographs of relatively transparent objects, such as leaves, by placing them in contact with a photographic plate and exposing through them. The shadow photographs obtained somewhat resemble X-ray negatives and reveal the structure of the objects in a manner determined by the varying transmission of light from point to point. Similar photographs have been made using infrared-sensitive plates, particularly by Plotnikow, who examined a large range of natural and artificial materials, including biological specimens, resins, metal foils, enclosures in envelopes, wood, and cloth. It was typical of most of the photographs obtained in this manner that they were very diffuse, an effect which was ascribed to scattering of the infrared by the objects studied. As a result of a survey of the scattering properties of many materials, liquids, and solutions, Plotnikow was led to regard the effect as a specific property of matter and called it the "longitudinal scattering effect." The magnitude of the scattering and its position in the spectrum were stated to be a function of the size of the molecules and the structure of the material. The larger the molecule, the longer was the wavelength

at which maximum scattering occurred. Further investigation will actually be necessary before it will be possible to state the true value of these observations in the study of the properties of matter. Details of the experimental method and the results of Plotnikow's investigations are to be found in papers listed at the end of this chapter.^{26, 71, 99, 102-111, 131}

MEASUREMENT OF INFRARED BY PHOTOGRAPHY

The intensity of infrared radiation can be measured by physical detectors which are sensitive to it; for instance, the bolometer and the thermopile, and by a photographic method. The photographic method is very convenient for measuring the intensity or the spectral distribution of intensity in the spectral region to which plates and films respond. The principles of photographic photometry or photographic spectrophotometry must be followed.^{53, 54, 70, 100} The most common use will be to measure the characteristics of a source of infrared radiation, or the transmission properties of materials and solutions in the near infrared.

With proper technique and intelligent interpretation of the results and a proper knowledge of the characteristics of photographic materials, photographic photometry is capable of a high degree of precision. Particular attention must be paid to wavelength sensitivity, intermittency effect, reciprocity failure, gamma-wavelength relationship, errors of development, and non-uniformity of effective sensitivity.

In photographic photometry the radiation whose intensity is to be measured is compared with that from a standard source by matching the densities of photographic images produced by both. It is practically impossible to compute energy directly from the measurement of a single density. It is possible, however, to use the photographic plate by a null method by which almost all of the disturbing variables are eliminated. In practice a single exposure is made to the unknown radiation, and an adjacent series of exposures is made to the standard, each exposure in the series being accurately known. The density in the standard exposure series which matches that for the unknown is picked out, and the intensity which produced it is also that which produced the density of the unknown. The conditions which must be fulfilled

in order that two samples of radiant energy may be stated to be of equal intensity have been defined clearly by Jones.⁷⁰ They are as follows: The exposures to the two sources should be made on small areas of the plate which are immediately juxtaposed; in no circumstances should exposures on one plate be compared with those on another, even if they are from the same box; the exposures should be made nonintermittently and simultaneously, and the times should be equal; the wavelengths should be equal; the densities must be equal. The methods for carrying out measurements under these conditions have been described by Jones, Harrison, Miller, and others mentioned in the bibliography.

In determining the spectral transmission of filters or dye solutions the principles of photographic photometry are employed for a number of wavelengths. Series of pairs of spectra are photographed on one plate or film. One member of each pair is a direct photograph of the spectrum of the source, while the other adjacent member is a photograph of the spectrum of the radiation from the same source after it has passed through the material under investigation. In passing from one pair of spectra to the next, the intensity of the direct spectrum is varied in a known manner while that of the unknown is held constant. In each pair it is possible to pick out a wavelength at which the densities of the two match, and, if the points so obtained in all pairs are joined, the curve shows the transmission characteristics of the material. This method is used in the Kodak Research Laboratories for measuring the infrared-transmission curves of filters, dye solutions, and so on, and is described in detail in a paper by Schoen.¹²⁷

COLOR PHOTOGRAPHY

In the modern types of film used for three-color photography, three superimposed emulsions are used, coated on one side of the support, or divided between the two sides. The layers are so sensitized that on exposure of the film in the camera or printer each of them records only one of the primary colors, red, green, or blue. In one type of process, cyan, magenta, and yellow dyes are formed in these respective layers during the processing of the film. In another form, the dyes are actually present in the

layers before the film is exposed, and they are removed or destroyed in part in the processing.

In order to be able to process the layers so that the dye images forming the final color picture are in their proper places, advantage is taken of special color sensitizing by itself or in relationship to the spectral transmission of dyes which might be in the layers. Some proposals have been made, particularly by Gaspar,⁴⁸ the Eastman Kodak Company,³⁷ and Kodak, Ltd., and Schinzel,⁷⁸ to use an infrared-sensitive layer which can be exposed by light which passes through the other layers, whether they are dyed or not, without affecting them.

In making photographs on multilayer color film, it has been proposed that the sound track be printed in an infrared-sensitized layer, separate from those carrying the color images.⁷⁸ In another case, it is proposed to include an interlayer of fogged emulsion which is developed to aid in confining the reversal exposures to their proper layers.⁷⁷ If this interlayer is made sensitive to the infrared, a negative sound track toned in gold can be introduced into the film without interference from the interlayer. In color films carrying sound records of dyes, it is necessary to select dyes having appropriate absorption in the infrared to which the photocells of sound reproducers respond.⁶⁷ Most dyes have high infrared transmission, and in the infrared region to which the commonly used caesium oxide cell responds, the sound modulation would be low and the noise level high. It is suggested in such cases that a photocell with response at shorter wavelengths⁵² be used. It should clearly be preferable to use an infrared-absorbing dye or other image in the sound track and a caesium oxide cell.

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Chapter XIII

CAMOUFLAGE DETECTION BY INFRARED PHOTOGRAPHY

Camouflage is a protective device intended to confuse or deceive an enemy observer who may operate from the air or from ground observation posts. It may be accomplished by a number of methods, the chief of which are complete concealment, blending the object with its surroundings, disruption of the apparent form of the object, and deceiving by the use of dummies or making the object appear like something else. It is applied to such things as matériel, troops, military works, aircraft, ships of war, airfields, and industrial plants.^{4, 14, 15, 20, 21, 24, 28, 35}

To be effective, camouflage must operate against direct visual observation and photography, particularly aerial photography. In a large number of cases, its purpose is to make the bombing of a specific target as difficult as possible. The bomb aimer is dependent on visual observation in using his sights, and the prime purpose of camouflage is to confuse him at the distance at which he must release his bombs to be effective. It is generally considered to be practically impossible to camouflage large installations in such a way that they will defy detection by photography from the air, and camouflage in such cases is carried out primarily for visual confusion. At the same time, it is certain that, if camouflage could be carried out to defy photographic observation as well, it would be worth while; much effort has been devoted to this objective. As the concealment becomes more effective, it becomes necessary to modify photographic methods of detection in order to cope with it.

The normal method of camouflage detection is to make what might be called "before and after" photographs, and in all cases to make overlapping pairs of pictures and examine them in the stereoscope. Interpreters have developed an uncanny sense for detecting details of objects in the stereoscope. To what extent

photography has been used in the detection of camouflage will naturally be made known only at the desire of the military authorities. It is possible, however, to make some statements about the principles involved, and we shall concern ourselves here only with infrared photography.

Although the simulation of natural foliage and grass is only one of the many aspects of camouflage, it is a very common one, and that in which infrared photography has to be taken into special consideration. It is a simple matter to find paints which are of the same color as natural foliage and grass and to use them on strips of canvas and other objects to imitate visually not only the color, but also the form of natural green objects. When they are photographed in the normal manner on panchromatic plates or films, they blend with the surroundings. It happens, however, that many common green paints which resemble natural chlorophyll visually or in an ordinary photograph have a very marked absorption in the infrared. They will, therefore, photograph as dark by infrared. Grass and foliage, particularly that of deciduous trees, appears light in an infrared picture. A mixture of natural green and an infrared-absorbing green paint will, therefore, be resolved by infrared as a mixture of light and dark. On the other hand, if a green paint is selected which has a high degree of reflectance in the infrared, it may be impossible to distinguish it from natural green in either an infrared or a panchromatic photograph. Such a paint would obviously be preferred for camouflage use.

In Figure 75 are reproductions of photographs of two green-painted canvas panels lying on grass and surrounded by trees. They were a close match in color, and matched the color of the grass quite well. As can be seen in the photograph made on panchromatic film, they do not show very much contrast against the background and trees. In fact, if they were broken up into strips and distributed among the branches of the trees, it would be difficult to distinguish them. In the infrared photograph, however, the situation is quite different. The panel marked *A* appears very dark, while the panel marked *B* is light. In this case, if they were broken up and distributed among the trees, it would be difficult to distinguish the right-hand material, but very easy to see the dark left-hand canvas.

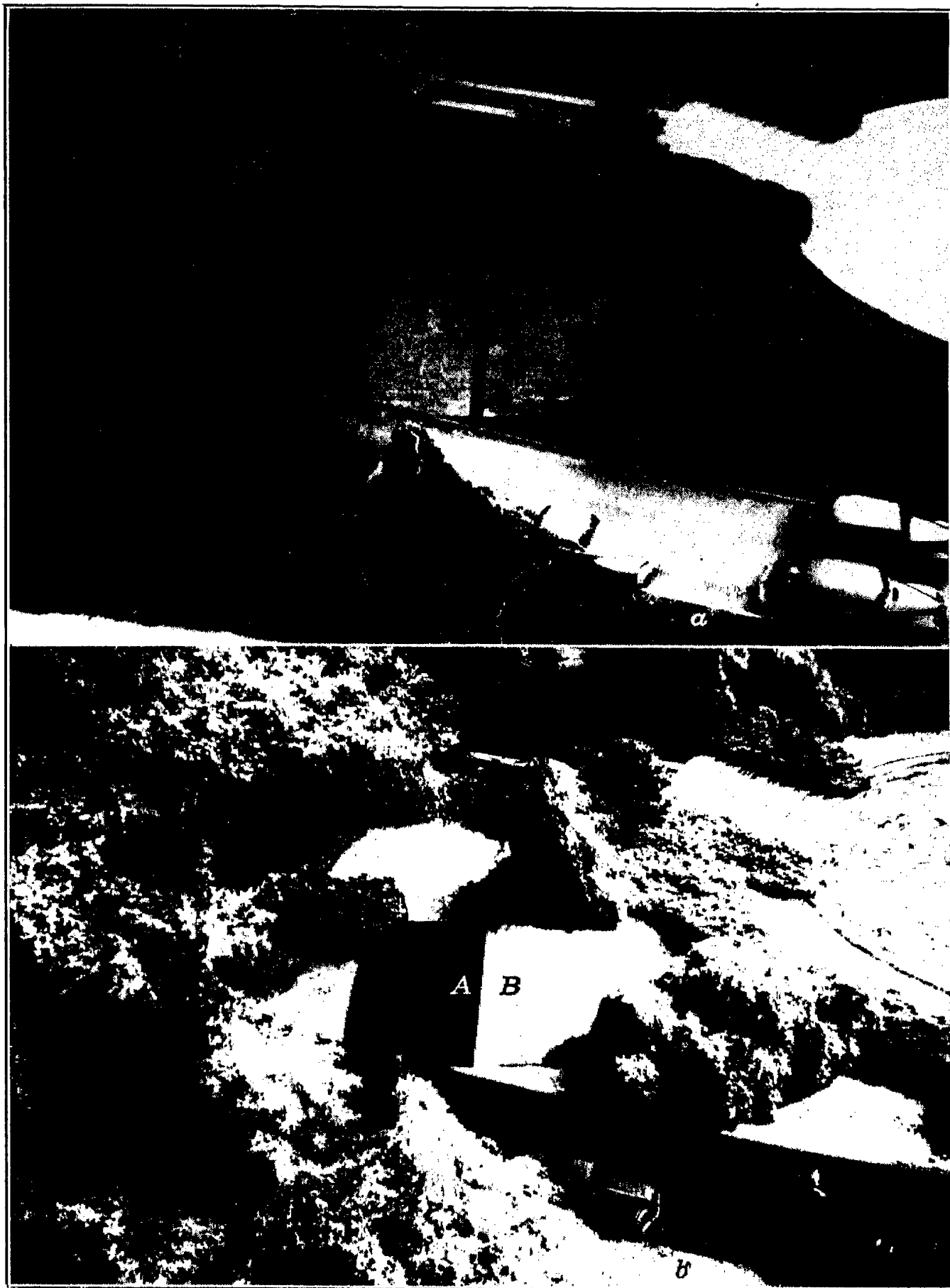


FIG. 75. Photographs of painted panels against a background of grass: *a*, on panchromatic film through a yellow filter, and *b*, by infrared.

The reason for this behavior of the two panels is that the left-hand one is painted with a green which strongly absorbs infrared, while the paint on the right-hand panel reflects it markedly. In a photograph by visual light, they are practically indistinguishable, whereas by infrared they show marked contrast. Spectrophotometric reflectivity curves of the two paints in comparison with a green maple leaf are shown in Figure 76, both in the visible and near infrared. It will be evident that one paint has reflectivity in the infrared closely resembling that of the natural leaf, while the other is more strongly absorbing. The reflectivity curves of different kinds of natural leaves resemble each other quite closely, as is evident from Figure 52.

A close examination of the curves in Figure 76 will indicate that, although the infrared-reflecting paint will appear practically as light as the leaf if photographed by light in a broad band beyond 7,000 Å, there are narrow spectral regions in which it shows marked difference in spectral reflectivity. Infrared-reflecting paints, in fact, can be classified into three groups, which can be designated *E*, *O*, and *L*, according to the aspect of their reflectivity curves. The *E* and *L* pigments are the so-called "early and late risers," the term referring to the position of the rise of reflectance as compared to that of chlorophyll. In the *E* (early) type the curve rises at shorter wavelengths than that for chlorophyll, whereas in the *L* (late) type the rise occurs at longer wavelengths than that of chlorophyll. Many known green pigments are of the *E* and *L* types. The class *O* pigments have reflectance curves which match more closely that of chlorophyll. Such pigments are known but are less readily available. Clearly they would be the most desirable pigments for foliage-green camouflage, for they would be indistinguishable visually and in all photographs.

Many specifications for green camouflage paints include particulars of the photographic testing method for ensuring adequate general infrared reflectance.^{19, 33, 36, 37} Usually, the paints are coated uniformly on metal panels with an underlayer which is part black and part white. They are then photographed together with standard panels which have known photographic infrared reflectance, one representing the upper and the other the lower limit of reflectance. In the photograph, the densities of paints

must fall between those of the standard limits if they are to be acceptable. The standards may be gray, or of any other color, provided that they have the proper infrared reflectances. In order to permit control of exposure and development, a neutral

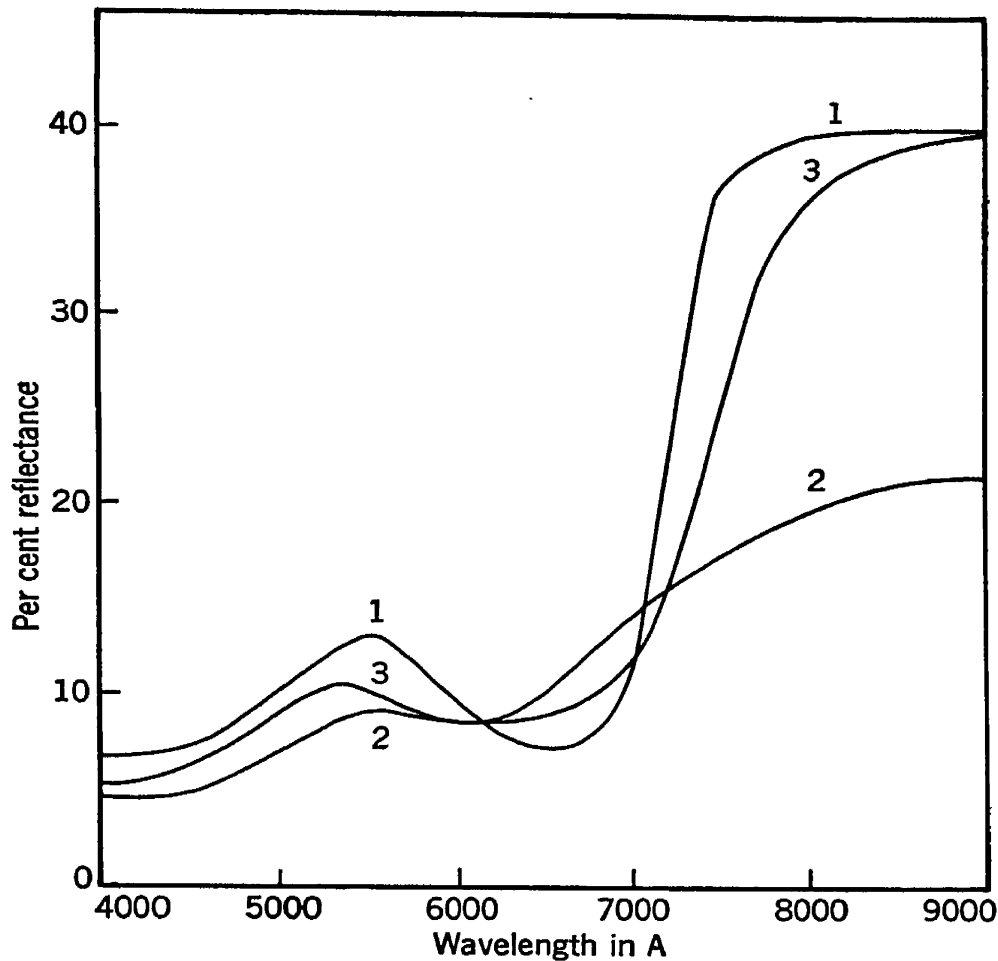


FIG. 76. Spectral reflectance curves of a leaf and two paints.

1 is a typical curve showing the reflectivity of a leaf in the visible and infrared. 2 is the curve for a green paint which absorbs in the infrared; it is the paint used for panel A in Figure 75. 3 is the curve for a paint which reflects the infrared; it is the paint used for panel B in Figure 75.

grey scale accompanies the paint panels and the standards. The paints should have a matte surface on drying down. The panels can be of any convenient size, but in practice it is found that a size about 3 by 5 in. is satisfactory.

The panels and gray scale are clustered closely together near the center of a flat board preferably covered with black velvet or black photographic paper. There are naturally many possible arrangements of camera, but miniature cameras should not be

used since the image size is too small to permit proper visual judgment. The minimum film size should be $2\frac{1}{4}$ by $3\frac{1}{4}$ in. The camera should be mounted so that it views the test panels perpendicularly, and the area of the film to be used for making the photograph should be a circle in the center of the film, the diameter of which is no greater than one third of the focal length of the lens. Tungsten-filament lamps should be used as the source of illumination, which should be so uniform that it does not vary by more than 5 per cent from one place to another over the area occupied by the panels. Film of the type of Kodak Infrared Sheet Film, having a sensitivity covering a range not less than from 6,800 to 8,600 Å, should be used, and the exposure should be made through the Wratten no. 89A filter.

Exposure and development should be such that at least five steps appear on the negative of the grey scale, if it is a Munsell Photographic Grey Scale with full value steps, or an Eastman Grey Scale. Two steps of the reproduced grey scale should be higher in density and two lower in density compared to the standard panels used. The development conditions should be those recommended by the film manufacturer.

After exposure and development of the negative, it should be examined against a diffuse illuminator, and the densities of the images of the sample panels should be compared with those of the two standard panels. If they are equal to either of these, or fall between them, the paint has satisfactory infrared reflectance.

Reflectometers and spectrophotometers may be used instead of the photographic method if they give results which would be obtained by photography. They have the advantage of simplicity if the proper instrument is available. The Hunter Multipurpose Reflectometer has been much used, equipped with General Electric barrier cells and the Wratten no. 88 filter. This combination gives results which parallel those obtained with Kodak Infrared Sheet Film and the Wratten no. 89A filter. The Hardy Recording Spectrophotometer has also been used. It gives a spectral reflectance curve from which infrared photographic reflectance values may be obtained by averaging the reflectance percentages measured at 30 selected ordinates.^{11, 36, 37} The ordinates are based on the transmission of the Wratten no.

89A filter, the spectral-sensitivity curve of Kodak Infrared Sheet Film, and the spectral-energy distribution of a specified tungsten-filament light source.

There is very extensive literature on camouflage, its photographic detection, the pertinent properties of paints and pigments, and of metals and other materials of construction, and the characteristics of natural colors. A select bibliography is given at the end of this chapter, and the reader should also consult Chapters VIII, X, XII, and XVI. Many paint manufacturers publish information concerning their camouflage paints, and the various branches of the armed services issue specifications for camouflage materials and colors for the use of paint manufacturers. According to Gardner,¹⁰ selection studies on pigments for making infrared-reflecting paints are not new. He mentions a statement from Wilford S. Conrow, national secretary of the American Artists' Professional League, to the effect that some studies date back to 1917, when nearly 2,000 pigments and colors were examined. From them there was selected a number of pigments which were developed into a formula for a dark-colored paint which had good infrared reflectance. Conrow reported that over 750,000 gallons of such a paint were made during 1917.

The earliest reference known to the author which gives spectrophotometric data pertinent to the camouflage paint problem is in the book on color published by Rood²⁷ towards the end of the last century. Rood shows typical visual spectral reflectivity curves of green leaves, with very high reflection in the extreme red, the narrow but strong absorption band in the red, the reflectivity hump in the yellow and green, and the absorption in the blue and violet. Rood states: "Green leaves are capable of reflecting a considerable quantity of red light, where surfaces painted with green pigments would not have this power, and consequently would appear black or grey." He actually described a dichroic filter resembling somewhat the Wratten no. 97 filter, through which green foliage appeared bright red, and most other objects appeared bluish, purplish, or violet. The Wratten no. 97 series of dichroic filters was put out in the First World War for the visual detection of camouflage. In addition to the reflection characteristics of leaves, Rood speaks of the properties of colored pigments in powdered form and coated in media.

In 1942, a United States patent was issued to Hexter and Shephard,¹⁸ assigned to the Arco Company, dealing with camouflage paints having desired visual characteristics and desired infrared-reflectance values, and, in particular, with paints which would match the color of natural foliage and have the high infrared-reflectance values of natural foliage. It deals with paint formulas having a dark visual color and composed of mixtures of pigments some of which have high infrared-transmittance values, above a wavelength of 7,000 Å. Where the base on which a paint is coated absorbs infrared the coating must have high infrared reflectance and low transmittance. Where the base is an infrared reflector, the coating may have high infrared reflectance or high transmittance. In this connection it is interesting to refer to a paper by Williams³⁹ in 1939 in which he showed that of two green paints one was a good reflector of infrared while the other was a good absorber. Other material of interest is described in Chapters VIII, X, and XII of this book. There is also a publication by the Walpamur Company³⁸ issued in 1940 dealing with camouflage paints sold by that company and pointing out the importance of high infrared reflectance.

Farnsworth⁸ in 1938 published the results of a photographic study of the infrared absorption of 48 paint materials, using the pigments dry and in different media coated on glass, paper, aluminum, and gypsum boards. She found that, with a few exceptions, the medium did not exert a great influence on the infrared photograph (see Chapter VIII).

In 1942, Blackmore³ published a lucid account of the principles involved in the selection of infrared-reflecting paints for camouflage purposes. He drew particular attention to factors which play an important part in determining apparent infrared reflectivity, in particular the need for high pigmentation in order to eliminate the effect of the surface on which the paint is applied, and the function of refractive index in determining opacity and therefore infrared reflectance. The medium plays an important part in the matter of refractive index. For instance, Ultramarine Blue has a much higher infrared reflectance in the dry state than when it is wet with a binder. Another factor which must be borne in mind is shading. Black, iron blues (Prussian, Chinese, Milori), and Chrome Green are "poisons" as far as infrared

reflectivity is concerned, and oxide reds and yellows are not good, although they may be used in the lower reflectance classes.

A further study of the infrared photographic properties of colors was made by Hart.¹² He used Kodak Infrared Film and the Wratten no. 87 filter, and 60-watt tungsten-filament lamps as the source of infrared. A grey scale was included in the field, and comparison photographs were made using panchromatic film. The interested reader is referred to the original paper for copies of a large number of the photographs. In general, it was found that white pigments such as titanium, zinc, lead, lithopone, and inert pigments show high infrared reflectance. Also included are colors such as lead chromate, zinc chromate, red lead, chromium oxide, precipitated iron yellow and iron red, ochres, Cobalt Blue, Ultramarine Blue, and several lake colors including many maroons, toluidine toners, and para reds. Colors which do not reflect much infrared include carbon black, Lamp Black, bone black, black iron oxide, Prussian Blue, phthalocyanine blue and greens, and Chrome Green. They photograph black or dark grey in the infrared.

A photoelectric method for evaluating the infrared-reflecting power of paint was described by Scofield.^{29, 30} From some points of view such a method is more suited to plant use where equipment and operative skill are not always available for precise photographic photometry. Using the Hunter Multipurpose Reflectometer as the instrument, Scofield recommended a combination of Wratten filters no. 89 and 44A to match the results obtained with the Wratten filter no. 89A and Eastman Infrared Film. Later, however, the Wratten no. 88 filter was recommended instead of the Wratten no. 89 and 44. Other instruments can naturally be used, but it is first necessary to calibrate them, and the best practice seems to be to determine per cent infrared reflectances as compared with magnesium oxide as the reference.

A most comprehensive study of the optical properties of pigments in the visible and near infrared was made by Vesce^{36, 37} and published in detail as Chapter 4 of Volume V of Mattiello's "Protective and Decorative Coatings." Vesce's work, and a "Report on the Optical Properties of Pigments in the Visual and Near Infra-Red" (see Endres⁶), were the result of the work of a Committee on Infra Red Fundamental Studies of Pigments and

Paints of the Federation of Paint and Varnish Production Clubs. The spectral characteristics were derived from both photographic and spectrophotometric methods, in the latter case the infrared photographic reflectances being computed by the selected ordinates method of Hardy¹¹ (see also Stearns^{31, 32}).

Vesce measured the reflectances in four bands of the spectrum: visual, 4,000–7,000 Å; border line, 6,800–7,000 Å; infrared 89 Å, 6,800–8,600 Å; and infrared 87, 7,400–8,600 Å. These bands were selected, because they can be measured conveniently by photographic methods and the results duplicated by spectrophotometric determinations. For the first band, Eastman Super-XX Panchromatic Film was used with the Wratten no. K-2 filter; for the border-line band, the Eastman Spectroscopic Plate Type S with the Wratten no. 89A filter; for the infrared 89A band, the Kodak Infrared Sheet Film with the Wratten no. 89A filter; and, for the infrared 87 band, the same film with the Wratten no. 87 filter.

The pigments for study were made in the form of briquettes in order to avoid the use of binders, vehicles, and extenders. In the photography, a briquette was arranged in the middle of a board measuring 14 by 20 in. and covered with black matte cardboard. The briquette was surrounded by a gridiron of Munsell Neutral Densities backed with Eastman Black Masking Chart Paper to avoid errors which might arise owing to infrared transparency of the neutral. A neutral photographic grey scale was arranged at the side of the field to permit control of exposure and development.

The board was placed face up on the bottom of the inside of a box 26 by 34 by 24 in. high, the inside of which was painted with a high-reflecting matte white paint. In each upper corner of the box was a 200-watt incandescent lamp in special reflector, furnishing 800 watts of illumination, giving a reading of 300 foot-candles on the test sample. In the center of the top of the box, which was lined with metal, was a circular hole, 16 in. in diameter. The plates and films were of 5- by 7-in. size, and a 14-in. Ektar lens operated at $f/27$ was used at 56 in. from the test panel, thus giving a reduction to one third. Development times for the different films and plate were chosen to give a

gamma of about 1.0, and all negatives were printed on a medium grade of paper.

The reflectance of a pigment sample could be ascertained by selecting visually or by a densitometer the particular standard grey (of known reflectance) which most nearly matched the test sample in the negative or print.

The photographic method of Vesce has been described in detail for the benefit of those who wish to make similar tests. It is not possible here to reproduce all of the results obtained by Vesce for they cover nearly 200 pigments. The reader should refer to the full publications for these. A few results, however, are given in Table XXV by way of example.

TABLE XXV

REFLECTANCES OF BRIQUETTE WAVELENGTH BANDS IN PER CENTS (VESCE)

<i>Color</i>	<i>Visual</i>	<i>Border Line</i>	<i>Infra- red 89A</i>	<i>Infra- red 87</i>
Crystal Violet Benzoate Lake	1.6	35.0	68.5	74.1
Fast Violet 4RN	1.7	8.6	21.3	26.1
Alkali Blue, green shade	0.7	1.8	6.6	10.4
Alkali Blue, red shade	0.6	1.9	13.6	22.9
Indigo Blue	2.8	5.4	44.2	57.2
Copper Phthalocyanine Blue	2.4	1.7	9.8	16.4
Chinese Blue	0.3	0.2	0.5	0.6
Prussian Blue	0.1	0.0	0.2	0.3
Ultramarine Blue	9.4	16.5	41.8	46.0
Phthalocyanine Green	5.2	1.8	3.1	4.4
Chromium Oxide, light	21.7	29.7	52.4	58.7
Chromium Oxide, dark	17.5	24.3	48.4	55.6
Hansa Yellow 3RA	38.5	87.3	90.8	91.9
Chrome Yellow, light	75.7	97.7	98.4	98.7
Permanent Red F4R	7.9	74.8	85.0	87.9
Madder Lake	6.6	57.4	74.8	80.6

In the abstract of the committee's report by Endres,⁶ there also are given lengthy tables showing the average infrared-reflectance values of pigments. Some values for the reflectance of pigments of particular interest to artists and the graphic-arts field are given in Chapter VIII, and the properties of some black paints are given in Chapter XVI.

It has been suggested that gasoline storage tanks exposed to the sun should be painted with infrared-reflecting paints in order to reduce their temperatures and the loss of gasoline by evaporation. A number of tests have shown that white or lightly tinted paints tend to reduce the temperature of the tanks. In wartime, however, they make conspicuous targets, and in some areas it would seem desirable to use paints of low visibility. Some early experiments of interest in this connection were reported by Williams.³⁹ He made photographs of painted panels by visible and infrared radiation and showed different reflection characteristics. He also noted the temperature rises of panels painted in different ways and irradiated by infrared. In a series of greens, in which there was very little visual difference, there was a big difference in the temperature rises. This matter was studied further by Gardner,¹⁰ using paints known to have high infrared reflectance. As sources of infrared he used infrared lamps and outdoor sunlight. Temperature rises and loss of gasoline by evaporation were measured, and it was shown that there is a definite advantage in the case of paints of high infrared reflectance, although whether it is significant or not remains to be proved by large-scale tests.

Johnson¹⁷ reached the following conclusions: The use of dark camouflage color instead of white or aluminum is likely to increase by at least twofold the heat absorbed from the sun's rays. The temperature increase which results will depend on the nature of the equipment and on specific circumstances. Certain types of camouflage paints can match certain types of surroundings visually and photographically. The principal justification for the use of infrared-reflecting paints arises from the photographic quality of the paint as compared with its surroundings, and to use such a paint where not needed would yield only a minor advantage in decreased temperature.

Infrared-absorbing paints on glass, applied for camouflage or blackout, might readily cause the glass to shatter when exposed to the sun's rays, and a knowledge of the infrared-reflectance characteristics would permit the choice of suitable paints. Similarly, it is important to have high infrared reflectance in coatings for dirigibles and in deck paints.

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Chapter XIV

PENETRATION OF RADIATION THROUGH THE ATMOSPHERE

GENERAL AND THEORETICAL

The earth's atmosphere is an envelope of gas consisting mainly of nitrogen and oxygen. In addition, there are smaller amounts of other gases, the chief of which are carbon dioxide, argon, neon, and other rare gases. There are also other substances, such as radioactive emanations, oxides of nitrogen, ozone, and particularly water vapor, present in varying amounts. Of these water vapor alone forms an appreciable percentage of the atmosphere, and the quantity present is dependent on the temperature. The higher the temperature, the larger is the amount of water vapor which the air can hold. The composition of the atmosphere near the surface of the earth, apart from its content of water vapor, appears to be essentially the same at all parts of the earth, although there is some change with elevation above the surface.

An atmosphere consisting only of gases and water vapor would be known as pure or clean air. The normal air, however, is never pure, for it contains innumerable particles of solid matter suspended in it. These particles come from the surface of the earth itself and from outer space, and are very varied in character. Dust caught up by the wind from the earth's surface or emitted from volcanoes is there in abundance; vegetable fibers, pollen, spores, bacteria, and other microscopic organisms permeate the atmosphere; fires emit considerable quantities of ash, and smoke in the form of particles of carbon, tarry matter, and other materials; the evaporation of the spray of the ocean leaves tiny particles of salt behind; dust of cosmic origin inhabits the upper layers known as the stratosphere; minute droplets are present owing to the union of water with gases produced by electric discharges, ultraviolet radiation, and the burning of coal. At times,

the water vapor present in the air manifests its presence in the form of droplets in clouds and fog, dew, rain, hail, and snow.

The beacon light of man is the sun. It brings him warmth, permits him to see, enables him to live. It is so intense a source and so near to the earth that it completely overshadows the light from the other stars and the reflected moonlight, and can be considered as the sole useful natural source of light. On its way to our eyes, the light which leaves the outer layers of the sun undergoes a variety of experiences. It has to pass through the earth's atmosphere. It strikes objects on the earth or in the air and is reflected and scattered by them, and, if this reflected light reaches the eyes and is bright enough, we can see the objects which turned it toward us.

If we look up to the sky on a clear day, but not directly towards the sun, we see an extraordinary thing. We might reason that we should see nothing at all, just blackness; but actually we see a blue sky. This is interesting, because the gases of the atmosphere do not glow and give out light of their own accord. The light from the sky must come to us from the sun itself. Sometimes clouds pass between us and the sun, or the sky is completely overcast, and the intensity of sunlight at the earth's surface is reduced considerably. At times a mist or fog obscures our vision of the sun or of objects on the earth which we can see on other occasions, or a blue haze may blur the detail of distant hills. At sunrise or sunset the clouds may appear to glow with an orange or red light. Even the sun itself at early morning or in the evening may appear of an orange color. And yet when the sun is high in the heavens it does not look orange, and the clouds seem white or grey. All these different things are very familiar to us, and the light by which we observe them all comes from one source alone—the sun. The varied effects are due to the passage of the light through the atmosphere.

Sometimes it may be an inconvenience that the atmosphere affects the sunlight so that we cannot see as well as we should like. The fog at sea is a source of real danger to the mariner; the airman may have difficulty in finding the airport and in landing his machine if there is a dense fog over the land; the driver of a locomotive may not be able to see his signals; the photographer may wish to photograph distant objects in sharp

detail and find they are obscured by fog or haze; the sailor may wish to take his bearings when the horizon and sun are obscured. Clearly, some method of countering the undesirable influences of the atmosphere and enabling us to "see" beyond the limits of vision of our eyes would be of great benefit to mankind.

In the attempt to provide such a method, many have turned to the use of photography, and it is of importance, therefore, to consider what the problem is and to what extent photography can help in solving it. First of all, we shall consider the nature and formation of the disturbing obstacles in the atmosphere, then the possibility of their being traversed by certain components of sunlight (or some artificial source of radiation), and finally whether any such components which do pass can be photographed in the camera.

The radiation which leaves the sun is actually changed to some extent by the gaseous constituents in the pure air. These are fixed, however, and our problem is to consider the radiation which passes through them, and the alteration which it undergoes as a result of the variable components, which are mainly nongaseous. The total thickness of the earth's atmosphere which it is necessary to consider as affecting solar radiation is less than 100 miles. The greatest effect is within a few miles of the earth's surface, where the layers containing the larger particles of impurity exist. In Chapter VII, which deals with the characteristics of sources of infrared radiation, some information is given concerning the general factors which affect the intensity of sunlight as it reaches the earth's surface. It should be read in conjunction with the present chapter.

DUST, SMOKE, HAZE, MIST, FOG, AND CLOUD

Dust consists of small solid particles of mineral or organic matter picked up from the earth's surface and distributed by moving bodies of air such as winds and convection currents. The so-called "volcanic ash" is dust ejected explosively from volcanoes and distributed by the wind. In addition, there may be dust in the form of fine ash given out from fires of all kinds, and meteoric or cosmical dust which consists of the ashes, as it were, of meteors burned in their passage through the upper atmosphere.

Dusts are usually formed by disintegration or dispersion processes.

The nature of the particles which can be called dust is very varied, and there is also considerable variation in their sizes. In general, the diameter of dust particles can be considered to be bigger than $10\ \mu$,* although much of the volcanic dust is smaller than this. The dust suspended in the higher atmosphere after the eruption of Krakatoa in 1883 and later eruptions of other volcanoes was of the order of $1.82\ \mu$ in diameter, and remained suspended in the air from one to three years. Measurements made on mineral dusts obtained by disintegration in industrial and mining operations show them to be, in general, smaller than $4\ \mu$ in diameter. Particles of dust normally settle in still air.

SMOKES are particularly predominant over industrial areas. They may be caused by the burning of coal, in which the heat causes decomposition of part of the fuel and liberates gas and volatile tar which, in turn, may be further broken down to carbon in the form of soot. The true smokes are formed by chemical reactions or by the rapid dilution and cooling of the vapors of substances of high boiling point. They are formed by condensation or aggregation, whereas the dusts are formed by disintegration or dispersion. The particles in smoke are usually solid and much smaller on the average than dust particles. According to the data which have been published, they may cover a range of sizes from $0.001\ \mu$ to $1\ \mu$, according to the way they are formed. The majority appear to be between $0.1\ \mu$ and $1\ \mu$ in diameter. Tobacco smoke has particles $0.2\ \mu$ or smaller in size, whereas the particles from burning oil may range up to $1\ \mu$ or more in diameter. The small smoke particles do not settle in still air, since they are in rapid Brownian motion and diffuse fairly rapidly. Certain types of industrial fumes, which might be considered as smoke or dust, are of exceptional size, ranging up to $100\ \mu$.

The number of particles of dust and smoke present in the air varies enormously with the locality and the conditions and may

* It is convenient to denote the size of small particles in terms of the micron (μ) as the unit. $1\ \mu$ is equal to $0.0001\ \text{cm}$ ($10^{-4}\ \text{cm}$), or $10,000\ \text{\AA}$. A smaller unit, the millimicron ($m\mu$ or $\mu\mu$), is the $1/1,000$ part of a micron and equal to $0.000,0001\ \text{cm}$ ($10^{-7}\ \text{cm}$) or $10\ \text{\AA}$.

range from about 500 to many millions of particles per cubic centimeter.

HAZE. The so-called atmospheric "haze" consists chiefly of dust and smoke particles. Its density increases with the number of dust or smoke particles in the air. Very thin high clouds of water or ice may also give the effect of haze. There is another kind of haze called "optical haze" which is due to irregular temperature distribution in the air and not to the presence of material particles.

MIST, FOGS, AND CLOUDS consist of drops of liquid suspended in a gas. Normally the liquid is water and, of course, the gas is air. There is no rigid distinction to be made among mist, fogs, and clouds. A mist can be regarded as a thin fog of relatively large particles, whereas a cloud differs from a fog only in the way it is formed and its position. A cloud is usually suspended in the air, whereas a fog is on or near the ground. Bancroft⁷ expressed it well when he said: "For most purposes it is sufficient to say that a cloud becomes a fog when one is in it." There is, further, no dividing line between fog and rain, rain merely being due to the formation of larger water drops which fall with perceptible speed. In the following discussion, if the word "fog" is used, it should be taken to apply also to clouds.

The source of the water which forms a fog is the water vapor of the atmosphere. To obtain a fog, the conditions must be changed so that the air will not hold all the water vapor originally present in it. The excess separates out as tiny droplets. The conditions essential for the production of fog are well known, and were first shown by the pioneer work of Aitken,³ Thomson,¹⁰⁷ and Wilson.¹¹⁶ In order that a fog may form, it is essential that the atmosphere be humid and that there be "condensation nuclei" present. At a particular temperature the air can normally hold a certain amount of water vapor. If it is thus full of moisture it is said to be "saturated." Sometimes it is possible to exceed this amount, and the air is then said to be "supersaturated." The water vapor which exceeds the amount required for normal saturation is always tending to deposit, however, and it will do so readily if the air contains suitable condensation nuclei.⁸ It will condense on them, forming sheaths of water about them as small droplets. Under certain circumstances the excess water

vapor will separate as a cloud of drops even in perfectly clean air containing no particles to act as nuclei. This will happen, however, only if the air is supersaturated to the extent of some eight times the amount of water vapor required for normal saturation. Since such a degree of supersaturation never occurs in any natural meteorological process, there is no reason to believe that fog and cloud can form spontaneously in absence of nuclei in nature.

The air is normally plentifully supplied with condensation nuclei, for they are provided by the particles which are in suspension in it—sea salt, dust, smoke, and so on. Electric ions also can act as condensation nuclei. This property is utilized in the well-known Wilson cloud chamber for showing the path of positively and negatively charged particles by the train of ionized air molecules which they leave behind. Water condenses on the ions and leaves a cloud which can be seen. In order for water vapor to condense on an ion in air, however, it is necessary that the air be supersaturated to about four times if the ion has a negative charge, or about sixfold if the charge is positive. Again, there is little reason to believe that such degrees of supersaturation occur in the atmosphere, so that condensation on electric ions does not give rise to the formation of natural fogs and cloud.

Fogs and clouds must, therefore, be due to water vapor condensing out of the atmosphere onto particles suspended in it, which act as condensation nuclei round which water droplets form. Whether a fog will form depends on the degree of saturation or supersaturation of the air and the nature of the particles present.

The degree of saturation of the air is dependent on its temperature. At lower temperatures the amount of water vapor required to saturate a certain volume of air is less than it is at higher temperatures. If we have a volume of air which is saturated or not, and suddenly lower its temperature, the amount of water vapor present may become higher than that necessary for saturation at the lower temperature. The excess will thus condense out as droplets on the nuclei present. In this way fogs and clouds are formed. For instance, if a layer of warm air over the sea, saturated with water vapor, drifts over a cold surface or comes in contact with a layer of cold air, a fog will form. In

this manner the fogs off Newfoundland are formed, the saturated warm air from over the Gulf Stream being cooled by drifting over the Labrador Current. Fogs are also formed near rivers, in valleys, and in cities, when the air carries much moisture owing to evaporation of water in the daytime and comes into contact with a low layer of air on the ground which has been cooled by radiation at nighttime. Clouds are formed by a variety of causes, but usually by forced or thermal convection so that bodies of air of different temperatures are mixed.

One way in which air can be cooled is by sudden expansion. This principle is employed in the Wilson cloud chamber and is used in mechanical refrigeration machines and apparatus for liquefying gases. If the air is at or near the saturation point and becomes suddenly expanded, as by passing into an area of lower pressure, it will be cooled somewhat and become supersaturated, and the excess water will condense out on nuclei present.

The diverse kinds of material particles which are suspended in the air are not equally effective as nuclei for producing fogs. One of the main differences lies in the fact that they are not all equally hygroscopic. A hygroscopic material is one which has an attraction for water molecules. Phosphorus pentoxide, sulphuric acid, calcium chloride, and similar materials which are used for drying depend for their action on the fact that they take up water, that is, they are hygroscopic. There are several materials in the air which are hygroscopic, such as tiny grains of sea salt and sulphuric anhydride formed by oxidation of sulphur dioxide liberated from furnaces and fires in cities and industrial centers. Such hygroscopic materials are very powerful as condensation nuclei and predominate over other particles which may be present. They are effective at very low degrees of supersaturation, and may even cause condensation of moisture from unsaturated air. When particles are not hygroscopic, their ability to act as condensation nuclei depends on their shape. In general, it may be stated that a nucleus promotes condensation of water vapor upon itself when it produces a diminished pressure of the vapor in contact with it. For a fuller discussion of this subject the interested reader is referred to the publications listed in the bibliography at the end of Chapter XV.

The atmosphere thus contains in suspension free solid particles or particles which have acted as condensation nuclei and formed droplets of water about themselves. Their relative amounts will depend on the degree of saturation of the air and the temperature, as well as on the location. The droplets in fogs and clouds are usually quoted as lying between about $1\ \mu$ and $50\ \mu$ in diameter, although larger droplets may be present in clouds, and rain droplets may reach a diameter of about one-half centimeter.

TABLE XXVI

APPROXIMATE DIAMETERS OF PARTICLES SUSPENDED IN THE ATMOSPHERE

Smoke.....	Smaller than $1\ \mu$. Tobacco smoke, $0.2\ \mu$ or less; smoke from burning oil, up to about $1\ \mu$; general, 0.001 – $0.1\ \mu$.
Fumes.....	0.1 – $1\ \mu$, but in the case of industrial smelter fumes may range up to $100\ \mu$.
Haze.....	Less than $1\ \mu$, generally 0.001 – $0.1\ \mu$.
Dust.....	$1\ \mu$ and bigger, but generally larger than $10\ \mu$. Dust from rock drilling, majority below 2 – $5\ \mu$, but many over $10\ \mu$. Volcanic dust from Krakatoa, $1.82\ \mu$.
Fog, cloud.....	5 – $50\ \mu$.
Mist.....	50 – $100\ \mu$.
Drizzle.....	100 – $400\ \mu$.
Rain.....	400 – $4,000\ \mu$.

These values are only approximate, since much depends on the nature of the particles, the mode of formation, and the state of disturbance of the atmosphere.

It is a matter of everyday observation that the transparency of the atmosphere depends on the presence or relative absence of the particles and water droplets. Clouds may obscure the sun and fog the landscape. Haze may blur the outline and detail of distant objects. The smoke from a forest fire or a chimney will appear as a cloud. It is of importance for our problem to find out whether these things which limit our vision can be penetrated by radiations which we cannot see, and, if so, whether we can record them on a photographic film and so “see through” the obscuring media.

The penetration of radiation through suspensions of small particles has been the subject of an enormous amount of study,

both by mathematicians who have investigated it from the theoretical point of view and by experimentalists who have sought to substantiate or disprove the theoretical work by actual observation.

There are five chief influences which may affect such penetration. They are known to the physicist as absorption, refraction, reflection, diffraction, and scattering.

In absorption, the radiation falling on the suspended particles is actually taken up by them, in whole or in part, according to their nature. In effect it disappears, and is usually converted into heat and tends to warm up the particles a little.

In refraction, the radiation passing through the particles is bent to one side and so emerges in a path different from that by which it entered.

In reflection, the radiation is deflected by the surfaces of the particles.

In diffraction, the path of the rays is actually bent when they pass close to the small particles. Its effects are sometimes seen as the corona around the sun or moon when there is a thin layer of clouds in the higher atmosphere.

In scattering, the small particles become in effect new radiators for the radiation, re-emitting it in all directions.

In refraction, reflection, diffraction, and scattering, the radiation is turned aside and given a new direction. The forward intensity of a beam is thus diminished, and the effects can be grouped broadly under the heading of diffusion. This diffusion cuts down the detail of distant objects and reduces visibility. Of the various effects classed as diffusion, only scattering shows useful preference for radiation of some wavelengths as compared with others, and is worth considering in detail in connection with our problem.

The actual amount of water present in a cubic meter of air in a dense fog is really quite small—less than 1 gram—so the true absorption of radiation by a normal fog of pure water droplets is quite small. It would require several miles of dense fog to equal a layer of water 1 cm thick, and even in this case there would be practically negligible absorption for wavelengths shorter than 14,000 Å. The absorption spectrum of water shows

no great absorption until this wavelength is reached (see Chapter XVI). True absorption, therefore, plays little part in determining the attenuation of light by fog until the fog is very dense, and then it is confined to beyond 14,000 Å. This applies strictly only to pure water fogs such as are found over the sea and waters away from industrial centers. Fogs over large cities may contain particles of smoke, and these will absorb light of all wavelengths strongly.

A good bibliography of atmospheric fogs and smokes covering papers published since 1900 has been issued by the Science Library in London.¹⁰⁰ Petterssen⁸⁸ surveyed the results of investigations of fogs which had been made in the years prior to 1941.

SCATTERING OF LIGHT BY SUSPENDED PARTICLES

Newton gave some consideration to the problem of the scattering of light by the atmosphere, and propounded a theory of the cause of the blue color of the sky. In the middle of last century Clausius^{25, 84} considered that the reduction of intensity when light passes through the atmosphere can be represented by the equation, $I = I_0 e^{-\frac{kd}{\lambda^2}}$, where I is the transmitted and I_0 the initial intensity, d , the thickness of the layer, λ , the wavelength, and k , a constant.

Observations of importance were made by Brücke¹⁸ in 1853, and particularly by Tyndall¹¹⁰ in 1869. They found that, when white light was passed into a transparent medium made turbid by very small particles, blue light was scattered away from the beam. Tyndall further found that the scattered light was polarized at right angles to the main beam. For a thorough investigation of the problem we have to thank Lommel, and particularly Lord Rayleigh,⁹⁰ who supplied the theory underlying the observations.

Rayleigh showed that, when a beam of radiation passes through a transparent medium carrying a suspension of particles whose refractive index is different from that of the medium and whose size is small compared with the wavelength of the radiation, some of the radiation is taken out of the beam and scattered in all directions from the particles. He formulated the important law

that the intensity of the scattered light varies inversely as the fourth power of its wavelength.

According to Rayleigh's law, if the intensity of the initial beam is represented by I_0 and that of the transmitted beam by I ,

$$I = I_0 e^{-k\lambda^{-4}x}$$

where x is the distance traveled through the uniformly turbulent medium, and $k\lambda^{-4}$ is the "coefficient of scattering."

It will follow that the shorter-wavelength blue light is removed more readily by scattering than red light which is of longer wavelength. The scattered light will, therefore, appear blue, whereas the directly transmitted beam will assume an orange or reddish color owing to the removal of blue from it. Rayleigh gave reasons for believing that the molecules of a gas such as air are able to scatter radiation in this way, and so explained the blue light of the sky. Near the surface of the earth there is extra scattering due to the matter in suspension, but most measurements made at higher levels above the earth's dust layer have been in general agreement with Rayleigh's theory of the cause of the blue sky. The theory also explains why distant haze and tobacco smoke appear blue, and we can also understand why the sun appears orange or red when viewed directly through smoke or haze—the blue from the sunlight is removed by scattering, and the residual colors of longer wavelength are not removed so much. The theory also shows that the dominant wavelength transmitted through the scattering layer becomes longer as the length of the path through it increases. This explains why the light of the sun inclines towards red about sunrise and sunset, since a longer path is traversed through the atmosphere. It also follows from the theory that, as the particles increase in size, less light of a particular wavelength gets directly through, and the predominant color of the light which does go through shifts to longer wavelengths.

Thus we see that, if we have in the air a suspension of particles whose size is small compared with the wavelength, and if we shine a beam of white sunlight on it, the red light will pass through it more easily than the blue, and, similarly, infrared radiation, which is of still longer wavelength, should pass more freely than the red. The larger the particles, the longer is the

wavelength of the radiation which will be turned aside by scattering, and correspondingly longer is the wavelength of that which passes through. If we wish to take a photograph through a haze which obscures a subject because it scatters blue light, we must therefore use red or infrared radiation which passes freely without being scattered. This is the principle employed in "haze cutting" in aerial and long-distance photography. Its application is discussed more fully in Chapter XII.

The preferential scattering of light of one color as compared with another color of longer wavelength is known as "selective scattering." Rayleigh's theory requires that the size of the scattering particles be smaller than the wavelength of the light. When the diameter of the particles is longer than the wavelength, true scattering no longer occurs, and the effect of the particles is of the nature of diffuse reflection, equally effective for all wavelengths. A number of papers have been published in attempts to express as a function of wavelength the transmission through suspensions of larger particles, such as those of fog.

Schuster⁹⁹ in 1905 pointed out that it is important to consider not only the scattering of the radiation coming from the original source, but also that of the radiation which has been scattered previously many times in the atmosphere, producing what is known as "self-illumination." The effect of this was worked out by King¹⁰⁵ in 1913 and has been considered in an excellent way by Cabannes²² in his book "*La Diffusion moléculaire de la lumière.*"

In the paper in which King dealt with the effects of self-illumination, he introduced an extra term into Rayleigh's equation to account for the light actually absorbed by the particles, or scattered nonselectively. His equation can be written

$$I = I_0 e^{-(a+k\lambda^{-4})x}$$

where a is the new term. King did not support his theory by actual observation on an atmosphere containing dust or fog, but he said that the effect of "atmospheric dust" could be taken into account in a simple manner by his equation. In 1931 Stratton and Houghton¹⁰⁴ pointed out that there is no theoretical justification for the application of King's formula to the case of a fog where the particles are larger than the wavelength of light.

In order to distinguish between the scattering by the molecules of the air and that by larger particles suspended in the air, we can rewrite the equation as

$$I = I_0 e^{-(a+b.f(\lambda)+k\lambda^{-4})x}$$

where the term $b.f(\lambda)$ accounts for the scattering by the suspended particles, and $k\lambda^{-4}$ refers to the scattering by the molecules of the air alone. If there are several different kinds of suspended scattering particles, it may be necessary to add several terms of the nature of $b.f(\lambda)$. Various values have been suggested for this function of wavelength, ranging from λ^{-4} for the smallest particles through a series of values λ^{-n} , where n decreases in general with increase in the particle size.

It is a difficult problem to investigate $f(\lambda)$ theoretically when the particles are not small compared with the wavelength, but it has received attention from many investigators. In 1931 it was studied by Stratton and Houghton,¹⁰⁴ who derived a new formula for the transmission of light through fog in an attempt to explain some experimental results they had obtained. Their development is based on the work of Mie,⁷⁸ Debye,²⁷ and Jobst,⁶¹ on the explanation of the colors of colloidal gold solutions in relation to the size of the gold particles, and on the pressure of light. Their equation is as follows:

$$I = I_0 e^{-2\pi n r^2 z K}$$

in which r is the radius of the particle; n is the number of particles per unit volume; K , the scattering coefficient, is a function of $2\pi r/\lambda$; and z is the length of fog traversed.

Figure 77 shows the curve of K as a function of $2\pi r/\lambda$. An examination of this curve shows that a transmission maximum would be expected at a value of λ which would make $2\pi r/\lambda$ equal to 11.2. In transmission measurements which Houghton had made on an artificial fog formed by the condensation of steam, he found a marked maximum transmission at a wavelength of 4,900 Å. This corresponds to a particle diameter of 1.75 μ (see Figure 78). The existence of a similar maximum in the wavelength transmission curve has been found by other workers in the case of artificial fogs having droplets of the same order of size.

With larger particles, such as those of natural fogs, in which the values of K fall in the region in which it is fairly constant, a maximum transmission in the visible would not be expected.

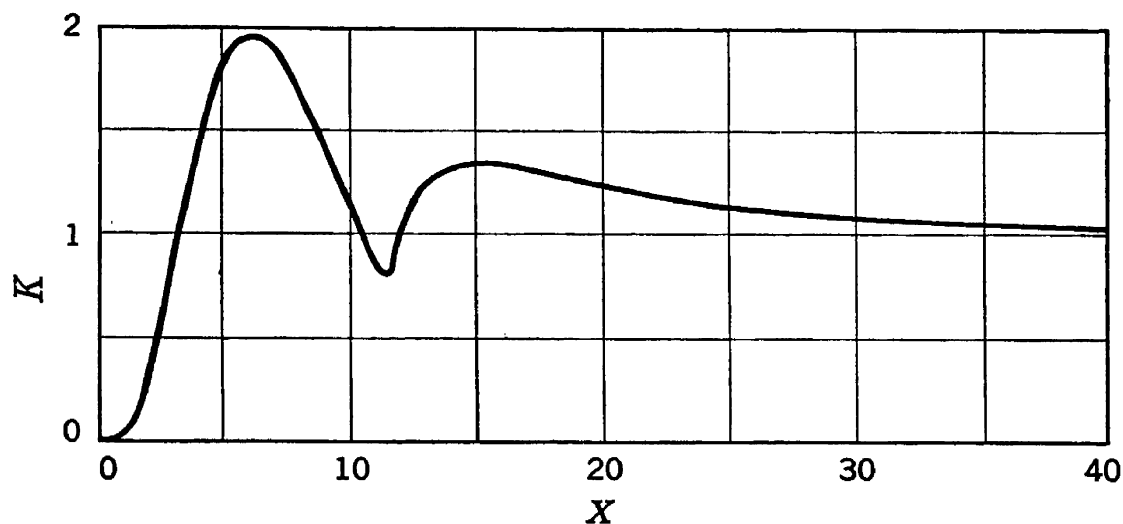


FIG. 77. Curve of K against $X (= 2\pi r/\lambda)$.

(From Stratton and Houghton)

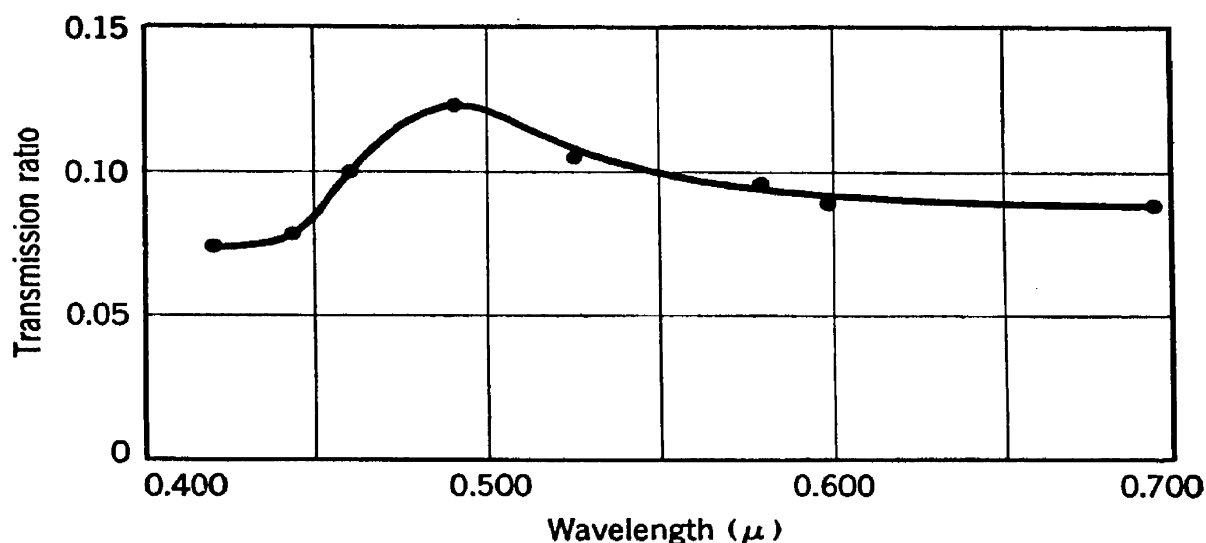


FIG. 78. Transmission of light through a fog of density 0.10.

The wavelengths are in microns ($1 \mu = 10,000 \text{ \AA}$).

(From Houghton)

When the radius of the particle is very small compared with the wavelength of light, the Stratton and Houghton formula becomes identical with the Rayleigh formula. Similarly, the equation of King becomes identical with that of Rayleigh when the losses due to light absorbed or scattered nonselectively are so small that they can be neglected.

Using the Stratton and Houghton theory, Foitzik^{34a} showed that the transition stage between dependence and independence of wavelength occurs for particle sizes between 0.5 and 2 μ . Clouds and fogs should thus show no selective transmission, and this in general is borne out by observation.

Harrison⁴⁷ discussed the mechanism of light scatter in the atmosphere and summarized the theory as given in the literature. He used this to determine the visual range under various conditions of scatter and extended it to calculate the "photographic range" for a variety of combinations of emulsions and filters covering the spectral range from the blue to the infrared. His results agree surprisingly well with some of the published data, for example, those of Hugon,⁵⁵ Hulburt,⁵⁷ and Mohler.⁸⁰ In general, he found that no increase in range would be expected when infrared emulsions were used if the visual range were less than one third of a mile, and at a visual range of 20 miles the increase would only be about 20 per cent.

The reader who is interested in a fuller discussion of this subject should read the papers referred to in the bibliography, particularly the book by Middleton,⁷⁷ and the articles by Harrison⁴⁷ and Breckenridge.¹⁸

BIBLIOGRAPHY

See end of Chapter XV.

Chapter XV

PENETRATION OF RADIATION THROUGH FOG AND HAZE

PRACTICAL OBSERVATIONS

It is now of interest to survey some of the actual observations which have been made on the penetration of radiation through fogs and haze and to consider the degree of success which can be expected in increasing the range of vision by photography with radiation of longer wavelength.

In order to see whether some wavelengths are transmitted better than others, experimenters have studied natural fogs out of doors, as well as artificial fogs produced in the laboratory. There is much variation in the significance of the results obtained, partly owing to the absence of a knowledge in many cases of the sizes and variation in sizes of the fog particles; partly owing to the way the measurements were made, some observers merely recording the "visibility" or "perceptibility" of distant objects, some using visual and others physical methods of measuring the intensity of light transmitted, some taking photographs of distant objects, some using relatively broad spectral bands obtained by the use of filters, and others narrow bands produced in the spectrograph.

We shall consider first of all some observations that have been made in the laboratory using artificial fogs, then physical or visual methods on natural fogs, and finally actual experiments made by photography through fog and haze.

ARTIFICIAL FOGS

Observations on a number of artificial fogs produced by condensing steam on particles of dust or other nuclei present in the air have shown in some cases a definite maximum transmission of light at a particular wavelength. Utterback¹¹¹ found such a

maximum in the green between 5,300 and 5,900 Å, although there seems to be some uncertainty as to the reliability of his measurements. Using artificial fogs of fairly uniform particle size from 2 to 3 μ in diameter and of various densities, Houghton⁵⁰ obtained a definite transmission maximum at about 4,900 Å (Figure 78), while Nukiyama and Kobayasi⁵³ found a sharp peak, at 4,800 Å for a fog of similar nature but probably of somewhat smaller particle size, and at 4,400 Å with a cloud condensed on nuclei of ammonium chloride. The theory of Stratton and Houghton (p. 382) gives some basis for the existence of such maxima.

Anderson⁶ made a comprehensive study in which artificial fogs were prepared by condensing water vapor on nuclei of tobacco smoke and of hygroscopic magnesium chloride mixed with tobacco smoke. The particle sizes were said to be 6 μ and 8 μ , respectively, and the transmission measurements extended from about 3,000 Å in the ultraviolet to 26,000 Å in the infrared. They showed a drop in transmission from 3,000 Å to 4,750 Å for the smaller particle fog and to 5,800 Å for the larger; from these minima there was a progressive increase in transmission through to the farthest infrared measured. The infrared transmission was somewhat higher for the small particles than for the larger ones and was many times that of the visible light. Other observations made by Külb⁶⁷ and by Müller, Theissing, and Kiessig⁸¹ also showed an increase in transmission of artificial fogs with increasing wavelength in the infrared.

NATURAL FOGS

Many methods have been used for studying the transmission of radiation through natural fogs, the actual selection in each case being determined by the purpose of the measurements. The results in general show a higher transmission in the infrared than in the visible region, but the superiority of the infrared is reduced when the particles become large and the visibility is low. This is evident from the observations of Benford,⁹ Michelssen,⁷⁶ Holmes,⁴⁹ Müller, Theissing, and Kiessig,⁸¹ Foitzik,³⁴ and Born, Dziobek, and Wolff¹⁵ (see also Harrison⁴⁷). Luckiesh and Holladay⁷³ reported no advantage in visibility of sodium lamps over tungsten lamps in foggy weather.

An important study was made by Granath and Hulburt⁴² and described in 1929. They used a light path of 400 m and covered the spectral range of 4,000–30,000 Å, the measurements at shorter wavelengths being made by photographic photometry, and those in the infrared by the thermopile. The observations were made on the edge of the Potomac River near Washington, D. C., and the fogs were described as having roughly the same optical characteristics as fogs at sea and along the coast. When the fog was of such a density that the visibility was only 600 m, the transmission over the path of 400 m increased from the violet to the infrared, as shown in Figure 79. Somewhat later Hulburt⁵⁶ extended the observations to 70,000 Å, and the extra value obtained is plotted in the figure. At this long wavelength the penetration through a thick fog (visibility 600 m) was somewhat better than at 30,000 Å, and this, in turn, penetrated more readily than visible light. In Table XXVII, taken from Hulburt's data, are given the distances, D , in meters, necessary to reduce the light to one hundredth of its original value, for various wavelengths (λ)—fairly dense fog, visibility 600 m.

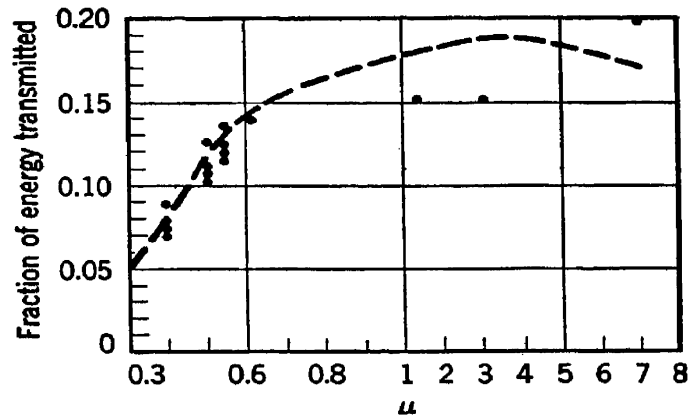


FIG. 79. Fraction of radiant energy transmitted through 400 m of fog of visibility 600 m.

The dots are observed, and the curve is theoretical (see text). Wavelengths are in microns ($1 \mu = 10,000 \text{ Å}$).

(From Hulburt)

TABLE XXVII

REDUCTION OF LIGHT INTENSITY BY FOG

λ in Å	4,000	5,000	6,000	10,000	30,000	70,000
D in m	710	843	910	970	980	1,140

Hulburt considers that the increased penetration of the infrared as compared with the visible light is insufficient to be of practical interest. In 1935 Hulburt discussed the subject again,⁵⁷ this time making actual photographs of a series of objects through

hazy and foggy atmospheres. His results are recorded in a later part of this chapter dealing with photographic observations.

Sanderson⁹⁷ extended Hulburt's measurements out to 120,000 Å and found that, with the particular fogs he used on the Potomac, the transmission curves were nonselective for wavelength when corrected for the transmission of clear atmosphere. Hayes,^{48, 102} on the other hand, using a special radiometer, showed that it was possible to measure infrared energy of wavelength longer than 30,000 Å through the worst conditions of atmosphere to distances considerably greater than the limits of visibility.

CORRELATION OF THEORETICAL AND EXPERIMENTAL OBSERVATIONS

It is of interest to see to what extent the formulas derived for the transmission of radiation through scattering media can be applied to the results of actual observations on fogs. Rayleigh's equation (p. 380) was derived on the assumption that the size of the particles was small compared with the wavelength of light, and there is no reason for expecting that it will apply to larger particles. It has been shown to apply satisfactorily to molecular scattering and explains such things as the blue light of the sky. In 1934 Pfund⁸⁹ described the results of some experiments made to test the validity of the law in the infrared, employing suspensions of zinc oxide and other materials which are transparent in the infrared. He found that the law was obeyed for small particles of zinc oxide, 0.088 μ in diameter, suspended in rubber, over the spectral range 8,000–24,000 Å. The transition from nonselective reflection to selective scattering set in when the wavelength was about equal to the particle diameter. Gamble and Barnett³⁷ also found agreement with Rayleigh's law in the appropriate size range. Clewell²⁶ worked out a scattering function for pigment particles describing scattering as a function of particle size over a wide range of sizes and indices of refraction, and reducing to the Rayleigh formula for small particles and for large particles of low refractive index.

A comprehensive attempt to correlate theoretical equations with experimental data was made by Breckenridge,¹⁰ using the formulas of King and of Stratton and Houghton (Chapter XIV). To these he applied the data obtained in fog-chamber measure-

ments by Utterback,¹¹¹ Anderson,⁸ and Houghton,⁵⁰ and the data on natural fogs by Karrer and Tyndall,⁶² Benford,⁹ and Granath and Hulburt.⁴² It is possible to fit the formula of King⁶⁵ to certain of the data on natural fogs, although the fitting of the curves is largely a matter of taste. The experimental curves representing the data obtained in fog chambers mostly show definite maxima or minima, and it is not possible to fit them to the King equation. The formula of Stratton and Houghton¹⁰⁴ was worked out to fit the experimental results which had been obtained by Houghton⁵⁰ on an artificial fog of fairly uniform particle size of 2–3 μ , and fair agreement was found.

In his paper of 1935, Hulburt⁵⁷ also showed that the data which he obtained with Granath could not be fitted to the Stratton and Houghton formula, if particles of one uniform radius were assumed. Two values of the radius were necessary, one large and one small. If appropriate pairs of values were selected, the theoretical curves agreed moderately well with the observations. For example, fairly good agreement was obtained assuming particles of 0.15 μ and 30 μ in one case, and 0.10 μ and 1.17 μ in another. The higher values agreed with measurements made on actual fogs, but meteorologists make no mention of fog particles as small as 0.1 μ . Hulburt, however, considered that his analysis was fairly direct proof of the existence of the small particles, and there seems to be no reason why small haze and dust particles cannot be present at times.

The characteristics of the transmission curves obtained from artificial fogs differ, in general, so markedly from those obtained on natural fogs that the fogs would appear to be essentially different in character, and it seems unwise to attempt to draw conclusions concerning natural fogs from studies made on artificial ones. For the most part the particles in natural fogs are somewhat larger than those in artificial fogs, in which case, according to the Stratton and Houghton theory, a maximum transmission in the visible would not be expected. In a private communication in May 1938, Professor Houghton informed the author that with Radford he had found constant transmission in the case of a natural fog, over the wavelength range 3,500 to 10,000 Å.

No natural fog could be expected to have particles of uniform size. It is well known in colloid chemistry that when a suspension of particles is formed by precipitation on nuclei the particles are distributed in size, usually according to a Gaussian or normal random-distribution function. It is exceedingly rarely that a suspension of uniform particle size can be obtained. Very few measurements of the distribution of sizes of particles in a fog have been made. The familiar corona method gives a value for the predominant particle size. The size-distribution curves can best be obtained apparently by actual measurement of the particle sizes in the microscope using an eyepiece micrometer or by measurement of photomicrographs.

Such measurements have been described by Houghton,⁵¹ alone and in conjunction with Radford,⁵⁴ for natural fogs. In the case of 40 fogs, the maximum in the size-distribution curve occurred at particle diameters ranging from 12 to 90 microns, with a marked predominance between 40 and 50 microns. In his 1932 paper, Houghton⁵¹ reported that the distribution curves had peaks at diameters corresponding to multiples of 6.2 microns. No such relationship was evident in his later observations. Incidentally, Houghton was concerned primarily with devising methods for dissipating fog to permit landing of aircraft in foggy conditions.⁵³ He worked mostly on the use of powders or solutions of hygroscopic materials, such as calcium chloride. A method which was successfully employed by the British during the war to permit landing of aircraft during fog, and designated FIDO, consisted in dispersing the fog by long rows of smokeless flames of burning petroleum oil.

STUDY OF PENETRATION USING DIRECT PHOTOGRAPHY

In order for an object to be visible, it must present some contrast to its surroundings.^{55, 60, 77} This contrast may be one of color or of brightness. We see a street lamp at nighttime, because it is brighter than its surroundings. We see a distant hill in daytime usually because it is less bright than the sky against which it is silhouetted. The distance over which an object can be seen is generally referred to by the meteorologist as the "visibility"; visibility is determined by contrast. The same applies

to what may be termed "photographic visibility," or the distance over which objects can be photographed.

In considering visibility it is necessary to distinguish between two types. One is exemplified by the street lamp, where the light by which we see it comes directly to our eyes. The intensity (flux density) of this will be decreased if the atmosphere between it and our eyes contains particles which scatter part of it away. If this loss is sufficiently great, the contrast between the light and the background may be so low that the eye cannot perceive it. The other type is represented by an object which of itself does not emit light, but which is visible because it is illuminated by some other source of light. A distant hill visible in daylight by virtue of the sunlight which it reflects is an instance. If there is a hazy atmosphere between our eyes and the hill, the light coming directly from the hill by reflection is reduced in intensity, but in addition to this there is interposed a luminous barrier, as it were, which is due to the haze scattering the sunlight falling on it. This luminous veil, superimposed on the light from the hill, tends to lower the contrast which enables us to see the hill and, if it is sufficiently bright, may render the hill invisible.²⁴

The contrast which enables us to see an object depends on many factors, but under favorable conditions it is about 2 per cent difference in brightness. One thing is quite certain, that contrasts which are invisible can be recorded photographically. For instance, let us consider two areas differing in brightness by 2 per cent but equal in other respects. They should be just recognizable as different in brightness. If they are photographed on a film developed to a gamma of 4, and if the exposure is such that it falls on the straight-line part of the characteristic curve, the difference between the brightnesses of the two areas will be four times 2 per cent, that is, 8 per cent. Likewise, if the brightness difference had been only one quarter of 1 per cent, and so invisible, it would just be visible in a photograph made under the stated conditions. A further enhancement of contrast would result from printing on a contrast grade of paper. The problem of visibility and the factors which determine it are of very great importance and have been the subject of much study and no little controversy. The interested reader cannot do better than refer to the excellent monograph by Middleton²⁵ entitled "Visibility

in Meteorology" for a thorough discussion of the subject and a full bibliography.

The problems attending photography through hazy atmospheres have a special significance for those engaged in survey and reconnaissance photography. They have been responsible for a great number of the studies made on the penetration of haze and fog by direct photography. They are of special importance in photography over long distances from the ground or from airplanes, and in vertical photography of the ground from airplanes. It is perhaps in the field of aerial photography that the greatest significance lies. At altitudes of 10,000 ft or more, the effect of haze is frequently so marked that it becomes very difficult to distinguish ground detail in the photograph, while the taking of long-distance pictures obliquely from an airplane is almost impossible without precautions for the elimination of haze.

Von Kujawa,⁶⁶ in an article on the requirements of film for aerial photography, gives an interesting diagram showing the distribution of intensity of the scattering effect of haze as a function of wavelength for three different angles of inclination of the camera. His curves are reproduced in Figure 80, 1 referring to vertical photography, 2 to an angle of 60° to the horizontal, and 3 to an angle of 50° to the horizontal. It is clear from this that the effect of haze is more pronounced in oblique photography than vertical and increases as the angle of obliquity increases.

The first comprehensive study of the effect of aerial haze on photography was described in a monograph entitled "Aerial Haze and Its Effect on Photography from the Air," issued in 1923 by the Research Laboratories of the Eastman Kodak Company.³² It describes work undertaken in 1918 by the Laboratories in collaboration with the Department of Military Aeronautics of the United States Army. The immediate object of the study was its application to military aerial photography. The monograph deals adequately with the principles underlying the measurement of aerial haze, and the essentials of the method of photographic photometry which must be employed in a proper quantitative study of the subject. Two types of observation were made, one relying on photography of ground test objects from airplanes, and the other on the photography in the laboratory of test ob-

jects which were veiled by light reflected from a partially reflecting mirror placed between the camera and the test objects to simulate the effects of haze.

In the study made from the air, the test objects consisted of large patches of black, grey, and white canvas, of known reflect-

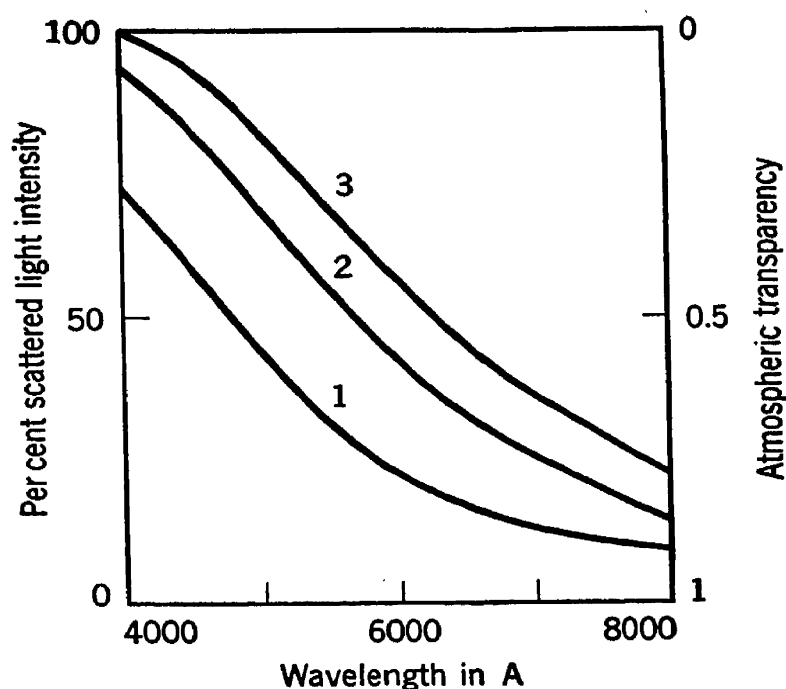


FIG. 80. Intensity of scattered light as a function of wavelength for various angles of inclination of an aerial camera.

Curve 1 is for the camera pointing vertically downward; curve 2 is for an angle of 60° to the horizontal; curve 3 is for an angle of 50° to the horizontal.

(From von Kujawa)

ing power, spread on the ground. These were photographed by means of a camera provided with four identical lenses, giving four similar images on four plates. Three of the lenses were usually provided with color filters, and the fourth carried an uncolored glass of the same dimensions as the filters. The apertures of the diaphragms of the four lenses were so adjusted as to give the same density of image on the four plates, when exposed to a uniform white surface illuminated by the sun.

After the exposures had been made from the air at different altitudes so that images of the three test objects appeared on all the developed plates, it was necessary to be able to relate the densities of the images of the patches to the exposures which

produced them. In order to do this, one of the lenses was removed from the camera and replaced by a glass plate having the same absorption and reflection characteristics as the lens. In the corresponding section of the plateholder, a compound step tablet was placed consisting of five strips having ten steps of known density, and provided with filters which were the same as those used in the other three lenses of the camera. The densities in each of the strips of the step tablet were so selected as to give good characteristic curves with the same times of exposure through the tablets combined with their filters. This meant that in the case of a light filter the densities were heavy, whereas with denser filters the steps were of lighter density. The exposure through the tablets was made to a white surface, illuminated with light of the same quality as that by which the photographs were taken, and the characteristic curves were drawn from the developed negatives. The densities of the images of the patches of cloth could thus be referred to the characteristic curve of the plate on which they were photographed, and the ratio of the corresponding exposure values derived. From these, the values of the effect of haze could be determined:

Let E_w , E_g , and E_b represent the exposure values in candle-meter seconds due to the white, grey, and black patches, in pure air or at low altitudes where the effect of haze can be neglected. At any altitude, let the exposure due to the light from the haze be e and let h' be the ratio of e to E_w , so that

$$h' = \frac{e}{E_w} \quad \text{or} \quad e = \frac{h'E_w}{E_w}$$

Then the total exposure giving rise to the image of the white portion of the subject will be

$$E_w(1 - a) + h'E_w$$

where $(1 - a)$ represents the absorption or subtractive effect of the haze. Similarly, the total exposure for the black portion of the subject is

$$E_b(1 - a) + h'E_w$$

and that for the grey portion is

$$E_g(1 - a) + h'E_w$$

This is true since the relative amounts subtracted and the absolute exposure added are identical for the white, grey, and black portions of the subject. Therefore, if, on a photographic material, exposed at any altitude, the ratio of exposures on the white and black objects, respectively, is K , then

$$\frac{E_w(1 - a) + h'E_w}{E_b(1 - a) + h'E_w} = K$$

or dividing both numerator and denominator by $E_w(1 - a)$ gives

$$\frac{1 + \frac{h'}{1 - a}}{\frac{E_b}{E_w} + \frac{h'}{1 - a}} = K$$

Now let $\frac{h'}{1 - a} = h$, and further let $\frac{E_w}{E_b} = C$, which is measured from near the ground, say, at an altitude of 500 ft. Then

$$\frac{1 + h}{\frac{1}{C} + h} = K$$

Solving for h gives

$$\frac{C - K}{C(K - 1)} = h$$

h is the haze effect expressed in terms such as are obtained readily from the photographic methods described.

From the characteristic curves of the plates through the various filters obtained by exposure through the step tablets in the manner described, the exposures corresponding to the white and black patches can be determined. In absence of haze, that is, at low altitudes, these are E_w and E_b , and their ratio is C . At other altitudes the corresponding ratio is K .

The values of the haze effect, h , can thus be determined in the course of flights at different altitudes, in a time so short that the atmospheric conditions do not change much, and for different spectral regions corresponding to the transmission regions of the filters used.

Exposures were made at altitudes ranging from 500 to 12,000 ft. Curves were drawn showing the relation between the haze value and altitude. They varied in shape, but three general forms of curve appeared adequate to represent the facts; they are shown in Figure 81. From the data obtained it was also possible to determine the spectral quality of the haze. The curve

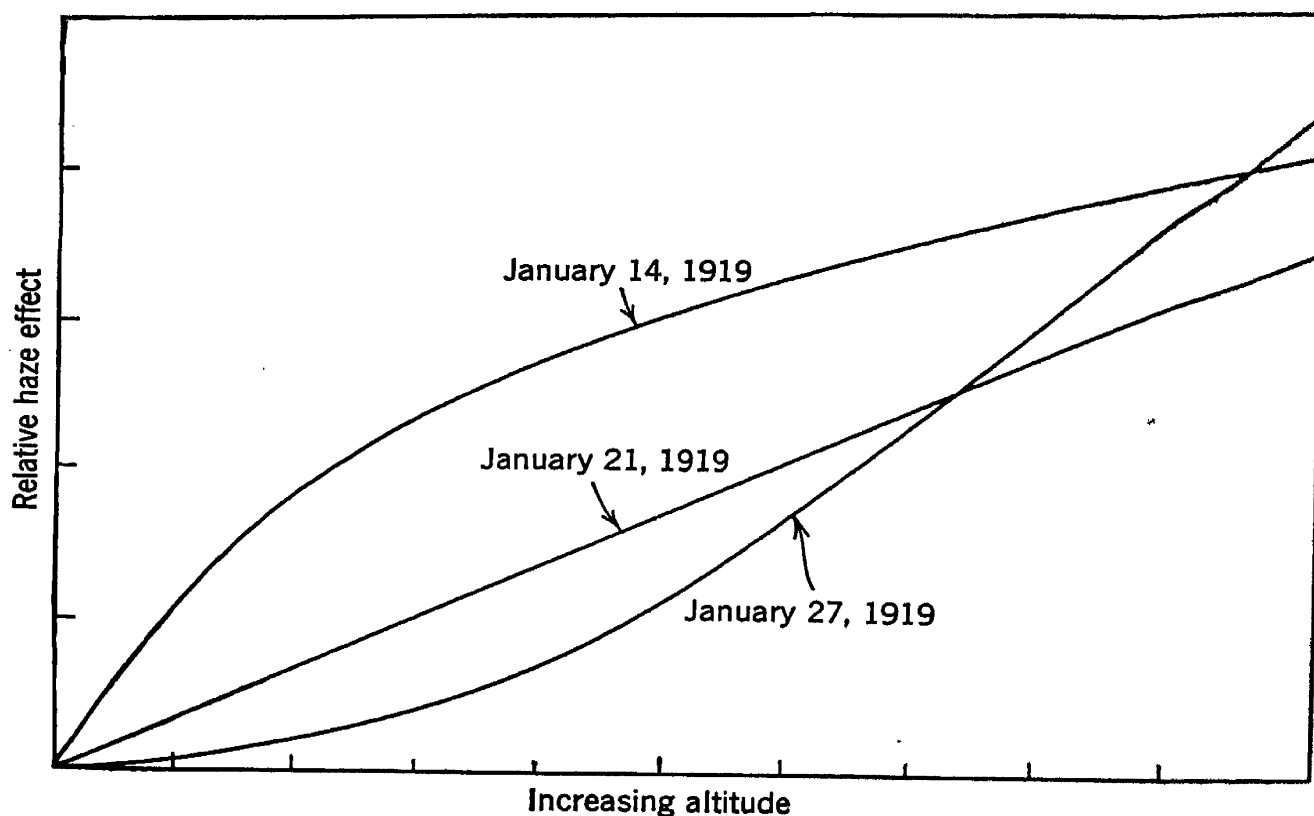


FIG. 81. Curves showing relation between haze and altitude.

shown in Figure 82 was derived from the haze-altitude curves for 10,000 ft, the transmission bands of the filters employed being rather broad, and ranging from 2,800 to 7,000 Å. This curve naturally represents only the particular haze conditions studied and is not corrected for any departure that the color of the white-canvas test patch showed from that of true daylight. It is, however, sufficient to show that a haze which is of significance in aerial photography is predominantly blue in color, and that in order to eliminate its effect it is necessary to photograph in light which is dark red in color, or even in the near-infrared region.

In the experiments made in the laboratory under conditions which simulated those obtained out of doors, a study was made

of the conditions governing the selection and use of photographic plates for photography through haze. It follows from the work and in fact is obvious from a general consideration of the problem that the photographic material employed must be capable of giving high contrast, in order that the greatest photographic contrast shall be given by the plate for a given subject contrast under the most unfavorable haze conditions. Since the haze is predominantly blue, the exposure must be restricted as far as

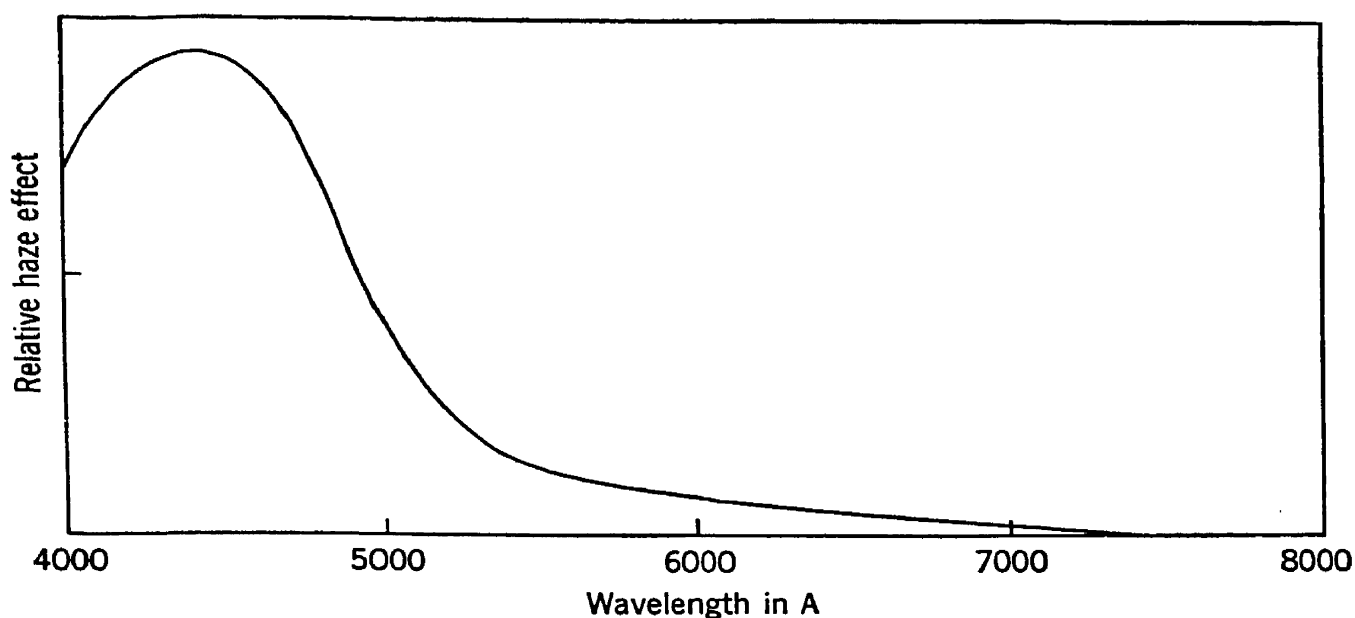


FIG. 82. Curve showing relation between haze and wavelength.

possible to the longer wavelengths, and the use of color-sensitive materials and color filters is required. In addition, the plate or film must be capable of good reproduction of fine detail under the degrees of enlargement which are often used in viewing or plotting from the photographs. This means that the material must have high resolving power and low graininess.

At the time these experiments were made, the panchromatic plates and films available were relatively slow compared to modern standards, and infrared materials of high speed were nonexistent, for even Kryptocyanine had not been discovered. In spite of these limitations, however, it was possible to draw conclusions which hold at the present time, but which can be followed much more effectively with the films available now.

When it becomes necessary to use filters in order to confine exposures to the longer wavelengths, the problem of the actual

exposure becomes of considerable import. Since all filters absorb some of the wavelengths to which photographic materials respond, their use naturally involves an increase in exposure. In the case of aerial photography, where the camera is moving in relation to the object photographed, there is an upper limit to the exposure which can be used if there is to be no blurring of the image due to movement. This is discussed in Chapter XII.

A number of investigators have published series of photographs of distant landscapes taken with radiation of different wavelengths. Typical are the results of Hugon,⁵⁵ who published a lengthy paper on the variation of the brightness of distant objects with distance. In application of a theory he had developed, he made exposures from the Observatory of the Pic-du-Midi, in the Pyrenees. On a day when the visibility was 70 km, the photographic visibility for light of wavelength 5,700 Å was the same, whereas, when the photograph was made with light of wavelength 8,300 Å, objects at a distance of 200 km appeared quite clearly. On another occasion, when the visibility was 40 km, it was increased only to about 60 km by photography with radiation of wavelength 8,300 Å.

In 1935 Hulburt⁵⁷ made a series of photographs to determine by direct means whether objects could be photographed through a fog by infrared over a greater distance than that at which they could be seen. Using the Eastman Spectroscopic Plate Type R, which was sensitive from about 7,200 to 8,500 Å, and the Type Q plate, sensitive from about 8,400 to 10,200 Å, he made a series of exposures on clear, hazy, and foggy days, noting the distance of the farthest object visible to the eye, and determining from the photographs the distance of the farthest objects recorded by infrared. His results are shown in Figure 83, in which plate visibility is plotted against eye visibility. The curves marked *Q* and *R* are for the Type Q and Type R plates, respectively, whereas that marked *P* is for photographs showing the same visibility as the eye and made with a panchromatic plate and the Wratten K2 filter.

It may be seen that the infrared plates gave a somewhat increased penetration compared to the eye, the increase becoming still greater as the haze grew thinner (that is, as the visibility increased). In the case of the Type R plates, objects were shown

at 0.5, 1.2, 4, and 8 nautical miles when the haze and fog were such that objects could just be seen at 0.5, 1, 3, and 6 miles.

The determinations of Hulburt were repeated and extended by Mohler,⁸⁰ covering the range of eye visibility up to 20 miles. She plotted the visibility given by the Eastman Infrared-Sensitive Plate Type 1-R (effective maximum wavelength about 8,200 Å) against that of the eye obtained by photographing on a Wratten Panchromatic Plate through the red Wratten no. 25 filter. (This latter procedure probably gives somewhat greater visibility than that of the eye which has its maximum sensitivity in the green, while the light used was red.) The curve had a slope which changed steadily from 1.1 on days of low visibility to 1.7 for the clearest days. There was striking agreement between points for hazy days and those for days of continuous or intermittent rain. The results agree with those of Hulburt in indicating that, the lower the visibility, the less is the increased penetration resulting from photographing by infrared. Harrison's calculations⁴⁷ showed good agreement with the results found in practice.

In May 1934 the present writer made a round crossing of the Atlantic to study the possibility of increasing visibility through fog at sea using infrared photography. Over 100 exposures were made, covering a wavelength range up to 10,000 Å, and the results agreed essentially with those of Hulburt and Mohler. The

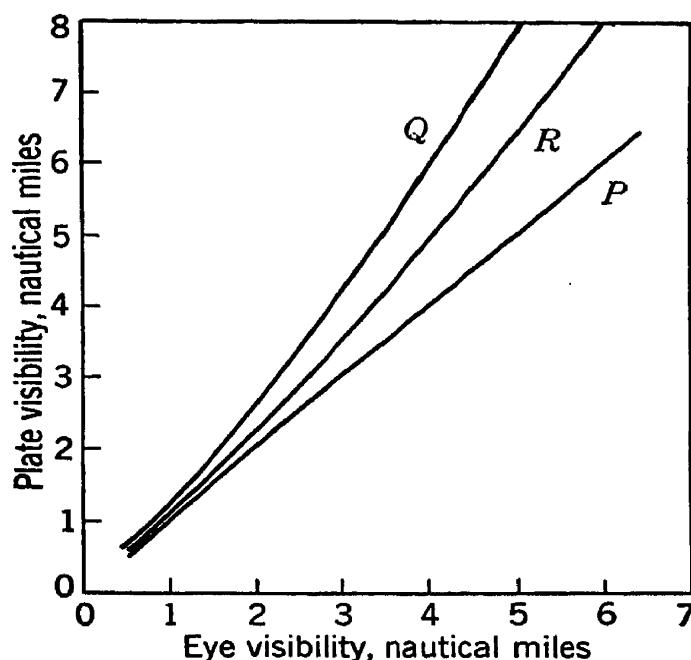


FIG. 83. Curves showing plate visibility against eye visibility.

Curve *P* is for a panchromatic plate and yellow filter, yielding a response similar to that of the eye. The curve is a straight line at 45° to the axis. Curves *R* and *Q* were obtained with Eastman Spectroscopic Plates, Types R and Q, sensitive in the regions 7,600 to 8,000 Å, and 8,400 to 10,200 Å, respectively.

(From Hulburt)

lighter the fog, the greater was the increase in penetration gained by using the infrared. However, in no case where the fog was a serious menace to navigation was there any advantage gained by the use of infrared photography.

A number of devices have been described and used for navigation and observation by means of infrared photography. The assumption has been made that infrared radiation will penetrate atmospheric suspensions which lower visibility. It has even been proposed that photographic sextants be made for recording the solar altitude when the sky is covered with cloud so dense that the sun's disk cannot be seen. As we have already shown, where the density of a fog is such as to constitute a menace to safe navigation, infrared photography is of no help. There are cases, however, where a relatively slight increase in visibility might be of importance. In naval operations, for instance, the maximum effective visibility is of importance, although with the advent of radar infrared photography has decreased in importance for this purpose.

Infrared cameras have been made in which it is possible to develop the film in a fraction of a minute, and from the point of view of reconnaissance this might be an important matter.

In this connection a patent by A. T. Stoyanowsky and Baird Television, Ltd.,¹⁰³ should be mentioned. A cinematograph camera photographs a subject from an aircraft moving in a horizontal direction. The film is immediately processed in the apparatus and the image viewed by the observer. The camera in the aircraft is oriented at such an angle to the perpendicular that the scene corresponding to the picture presented at any particular moment bears a definite relationship to the position of the aircraft at that moment. In this way it is claimed that a bomb, projectile, postal packet, or other missile could be dropped on a desired spot even though the spot were invisible. In actual practice, however, infrared photography will not permit the penetration of a fog which reduces atmospheric visibility appreciably, and it would appear that there are so many other factors involved that the chance of hitting a particular objective would be very small. Here again, radar would be used at the present time.

CONCLUSIONS CONCERNING THE PRACTICE OF PHOTOGRAPHY THROUGH HAZE AND FOG

From what has been said in this chapter and the preceding one it is possible to draw a few general conclusions about the possibility of penetrating haze, mist, and fog by infrared photography.

In general, it can be stated that a large increase in penetration can be obtained in the case of haze which is of small-particle size. Such a haze preferentially scatters light in the blue end of the spectrum and so appears bluish in color. The greater the visibility, the greater is the extent to which it can be increased by use of the infrared. There is, of course, a limit set by the curvature of the earth and the size of the objects it is desired to photograph.

In the case of mists, fogs, and clouds which are white or neutral grey in color and therefore show no preferential transmission for longer wavelengths in the visible part of the spectrum, no useful increase in penetration may be expected. Now and then a freak situation might occur, in which thin layers of mist alternate with relatively wide clear spaces, but such cases must be considered as exceptions.

The disk of the sun usually appears colorless when faintly discernible through a clean fog or cloud, and the illumination on cloudy days is not of a very different color from that on clear days. In such conditions, no increase in penetration would be expected.

In general, the lower the visibility, the smaller is the chance of increasing it by infrared photography. Theoretically, this presupposes that it is not possible to make photographic materials sensitive to very long wavelengths, say 200,000 Å, which would be necessary, according to Rayleigh's theory, for penetrating a fog of fairly large-particle size. There seems to be no chance of this being accomplished. Moreover, the energy in sunlight at these long wavelengths is so low as to render exposures impracticable, and at wavelengths beyond the present photographic limit other factors, such as true absorption by the water droplets, would come into play in addition to true scattering.

As far as the photographic film or plate is concerned, it must be as sensitive as possible in the infrared so that the short ex-

posures necessary in aerial photography can be achieved, it must be capable of giving high contrast, and it must have high resolving power and low graininess.

The characteristics of long-distance and aerial photographs used for survey purposes are described in Chapter XII, which should be read in conjunction with the matter presented here.

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Chapter XVI

OPTICAL CHARACTERISTICS OF MATERIALS IN THE INFRARED

During the course of this book, mention has been made of the manner in which many materials transmit and reflect the infrared. A knowledge of this is necessary for the intelligent application of infrared photography and satisfactory interpretation of the results. In this chapter are brought together data concerning other materials which might be of interest to the photographer, including a somewhat fuller discussion of the properties of lenses, filters, safelights, and common materials. It is not the intention to give extensive tables of the optical properties of materials in the infrared, but merely to select those which are of particular interest. For data concerning other materials the reader should consult the books of chemical and physical constants, particularly the "International Critical Tables," Volume V, Landolt-Börnstein's "Physikalisch-Chemische Tabellen," "Tables Annuelles de Constantes et Données Numériques," "Smithsonian Physical Tables," and references at the end of this chapter.

QUARTZ AND GLASS

Quartz is very transparent in the near infrared. Its transmission is practically complete up to a wavelength of 36,000 Å, after which it decreases to a very low value at 50,000 Å.^{10, 27}

Most colorless glasses, including window and plate glass, ultraviolet-transmitting glass and optical glass, transmit freely out to about 26,000 Å. Beyond this point they absorb in a manner determined by their composition. Crown glasses show the strongest absorption and flint glasses the least—with the exception of quartz, which has still less. The transmission of colored glasses in the near infrared depends on the nature and amount of the metallic oxides, silicates, sulphides, and colloidal metals which are added to the basic glass.^{32, 62, 78} Some of them have very

strong absorption in the infrared, and they are, in fact, deliberately made as heat-absorbing glasses. Unfortunately, the metallic salts which are added to produce absorption in the infrared also absorb in the visible region of the spectrum, so that there are no colorless glasses which are good absorbers in the near infrared. The optical properties of glass in relation to the composition are fully discussed in the books by Thiene⁷⁸ and Morey,⁶² to which the reader is referred. Another article of importance is that by Fritz-Schmidt, Gehlhoff, and Thomas,³² from which the following notes are abstracted:

Yellow glasses, obtained by the addition of salts of cerium, show no special absorption in the infrared other than that of the basic glass at about 26,000 Å and beyond. Yellow glasses sometimes are made with uranium salts, in which case they have marked absorption bands at 9,000 and 15,000 Å.

Blue-green glasses commonly contain iron oxides and show very strong absorption in the near infrared, usually centered about 11,000 Å. The transmission increases with wavelength to the region 25,000–40,000 Å, after which it rapidly decreases again. The degree of absorption and the breadth of the band increase with the increase in content of iron oxide, and they are greater with ferrous than with ferric oxide. The more efficient such a glass is for the purposes of heat absorbing, the deeper is its visual color. Green glasses containing chromium oxide, although strongly colored, are very transparent in the infrared in the same manner as the basic glass. Green glasses in which vanadium oxide is used have a strong absorption in the infrared around 11,000 Å, beyond which they are transparent.

The most important blue glasses contain cobalt or copper oxide. Cobalt blue glass usually has a high transmission in the blue and red, followed by a strong absorption between 10,000 and 20,000, centered around 15,000 Å. Copper oxide blue glasses transmit in the blue and green and show strong absorption in the visible red which extends into the infrared. It is particularly marked in the region 7,000–13,000 Å. The transmission becomes normal again at about 25,000 Å. Red glasses, containing manganese oxide, are generally quite transparent in the near infrared. The characteristics of some of these which are used as light filters are considered in the section of this chapter dealing with filters.

Red glasses containing nickel oxide somewhat resemble iron glasses in their infrared characteristics and show absorption bands at about 11,000 and 22,000 Å, with a transmission region between at 15,000 Å. The nickel and iron glasses are the best infrared-absorbing glasses, but they are highly colored (see Figure 89B).

LENSES

A simple lens made of one piece of glass is unable to bring all the wavelengths of a beam of white light to focus at the same point. The reason is that the refractive index of glass (that is, its power to bend light) is greater for shorter wavelengths than for the longer. A simple collective lens, therefore, focuses blue at a point nearer to it than that at which it brings red light to a focus. Infrared, being of longer wavelength than red, is focused still further from the lens. The separation of wavelengths, often called "dispersion," which occurs when light passes through a simple lens depends on the curvature of the lens, but if this is held constant the dispersion will differ according to the kind of glass used in the lens. By proper selection of different glasses and combining collective and dispersive lenses, it is possible to make lenses in which the focus is the same for more than one color, say, the blue and red. This process is called "achromatizing," and the result is an "achromatic" lens, of which the modern photographic anastigmat and the achromatic microscope and telescope objectives are examples. In achromatizing lenses for visual use, it is customary to correct the focus for wavelengths in the blue and orange-red at the F and C Fraunhofer lines of the solar spectrum, situated at 4,861 and 6,563 Å. Photographic lenses are generally achromatized for the G' and D lines, in the violet and yellow at 4,340 and 5,890 Å.

Any two wavelengths can be brought together in the process of achromatizing, but, when this is done, other points in the spectrum do not coincide exactly. There is left what lens designers call the "secondary spectrum." The results of this can be shown by drawing the "color curve" of the lens. Two typical color curves for achromatic lenses corrected for visual and photographic use, calculated for the author by Dr. Max Herzberger, are shown in Figure 84. They are drawn by plotting the focal-length correction against the wavelength. It will be observed

from the figure that, as the wavelength increases from the blue, the focal length gets shorter, passes through a minimum in the green, and then increases as the infrared is approached. The curve is steeper on the blue side than it is on the red. As the wavelengths increase into the infrared, the focal length gets pro-

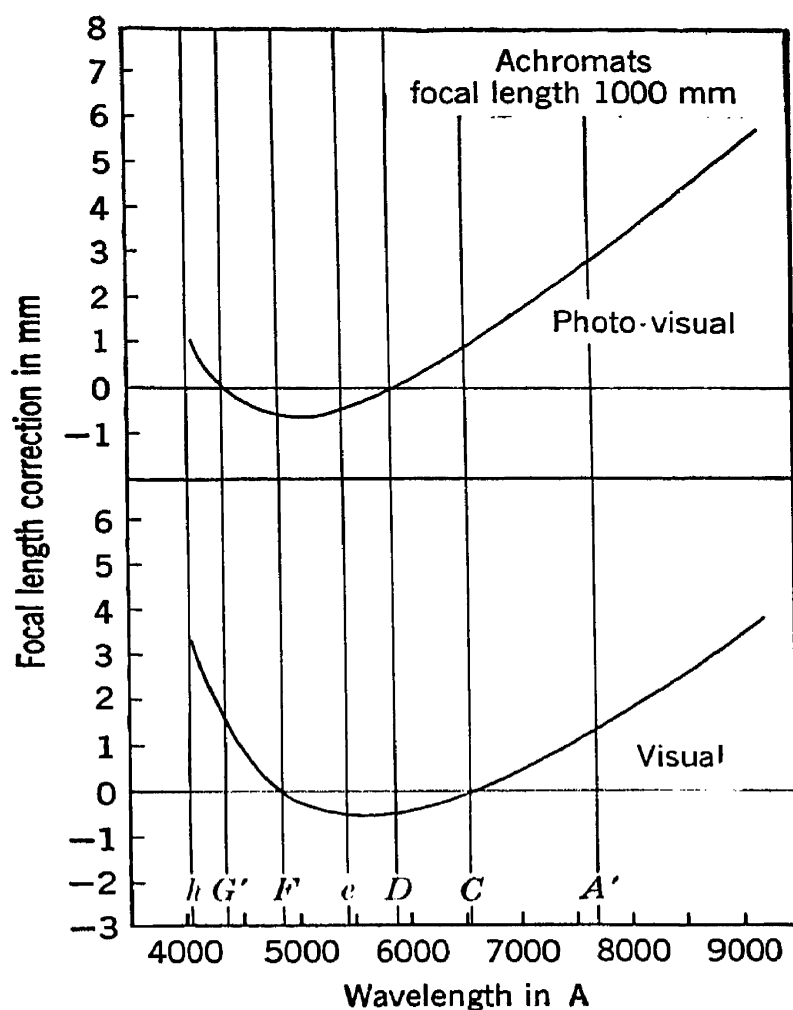


FIG. 84. Focal-length correction of achromatic lenses as a function of wavelength.

gressively longer, and so requires a correction of focus to be made, as explained in Chapter II.

There is a way of eliminating the secondary spectrum known to lens designers, and it is employed in the manufacture of the "apochromatic" lenses. In these, special glasses, or the crystalline mineral fluorite, are used to replace one of the glasses normally used in the construction of achromatic lenses. Fluorite is available only in relatively small pieces. The construction of apochromatic lenses of fluorite and even of glass is expensive, and so the lenses are not yet used for ordinary photography.

Apochromats of low aperture are sometimes used for photo-engraving and color photographic cameras, where it is necessary to have images of exactly the same size made by red, green, and blue light. Color curves for two apochromatic microscope lenses

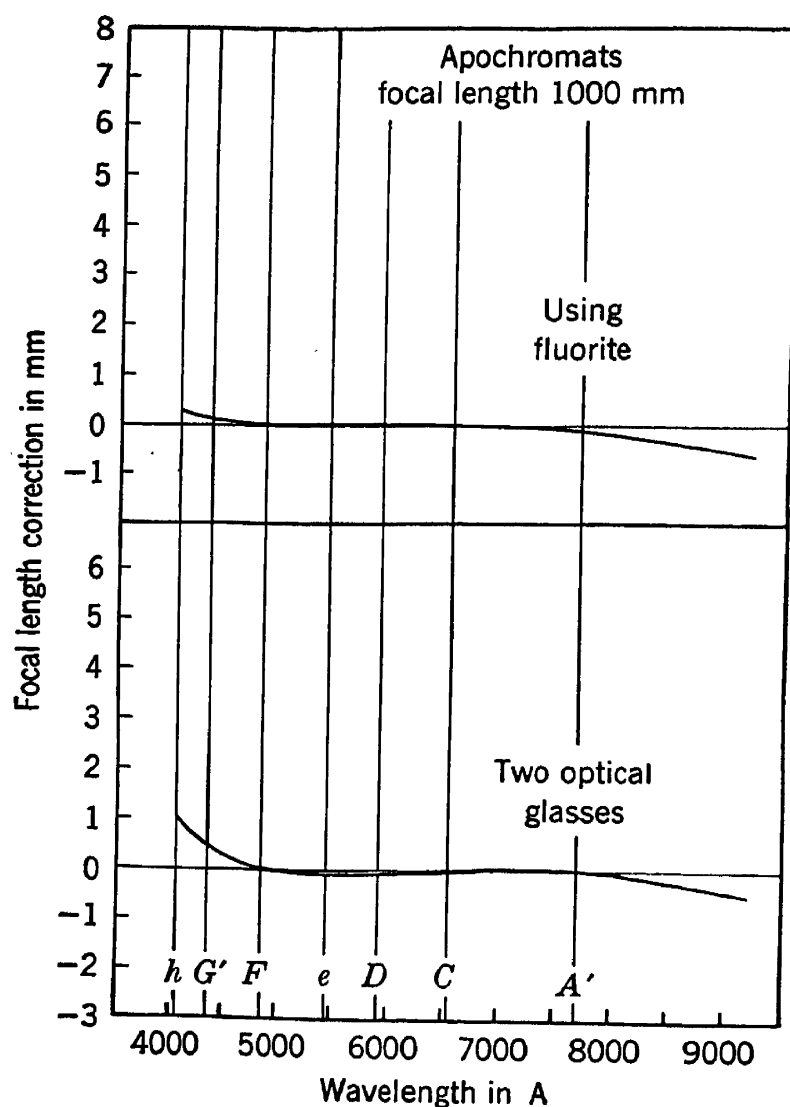


FIG. 85. Focal-length correction of apochromatic lenses as a function of wavelength.

are shown in Figure 85. These also were calculated by Dr. Herzberger. In their case, it may be observed that the focus is sensibly constant for all wavelengths in the visible from 5,000 to beyond 7,000 A, and that it does not depart in the infrared to nearly the same extent as in the case of the achromats (Figure 84). The apochromatic lenses are not perfect for use in the infrared, but they are clearly superior to the achromats.

The wavelengths for which lenses are achromatized are chosen deliberately. Those intended for visual use are so made that the minimum focus is in the yellow, to which the eye is most sensitive, the blue-green and red on each side of it being equalized.^{50, 70, 75} In the earlier types of photographic lens designed for use with plates and films which had their maximum sensitivity in the violet, and in mercury lamps which were very strong in violet, the correction was for the violet and yellow, so that, when they were focused by eye, they were in sharp focus in the spectral region to which the photographic materials responded. When panchromatic films and plates were introduced, particularly in conjunction with incandescent tungsten-filament lamps, some lenses were achromatized for the blue and red, because the photographic materials also responded to red, which was emitted in high intensity from the lamps. There has been much discussion as to the need for this, some designers insisting that it gives superior results with the high-aperture lenses used in cinematography, whereas others deny any advantage.^{29, 64} There is no doubt, however, that for infrared photography it is necessary to achromatize the lens in the infrared and visible spectrum, if no correction of focus is to be made after focusing visually.^{37, 46, 57, 74} Infrared materials are always used with a filter which absorbs violet and blue light and confines the exposures to the infrared. A lens corrected for use in this region of the spectrum should, therefore, be achromatized for the yellow and infrared, say, at wavelengths 5,890 and 8,100 Å, and this has been done by a number of manufacturers. In the case of such lenses, if the image is sharp when focused on the ground glass, it is sharp for photography by infrared. The focal-length shifts in the infrared for some commercial lenses are given in Chapter II.

In order to design a lens achromatized for the infrared, it is necessary to know the refractive indices of optical glasses in that region of the spectrum. The well-known Hartmann formula in general is not useful for interpolation into the near infrared. Surveys of the optical properties of glass, including characteristics in the infrared, are given in the books by Morey⁶² and by Thienc.⁷⁸ Measurements of the refractive indices of optical glasses in the infrared have been published by Rubens,⁷¹ Kings-

lake and Conrady,⁵¹ and Brauckhoff.⁸ Matossi and Bluschke⁵⁹ dealt with the infrared-reflection spectrum of glass. In connection with attempts to derive a formula by which the focal length of a lens for the infrared could be calculated from a knowledge of the focal length for a wavelength in the visible, Herzberger³⁸ made a study of the dispersion of glass in the visible and infrared.

Kingslake and Conrady⁵¹ calculated the color curve of a thin achromatic doublet lens using the values of refractive index which they measured. One curve was determined for a lens having a minimum focus in the visible spectrum at 5,550 Å, achromatizing for the F and C lines at 4,861 and 6,563 Å. Another was calculated for photographic use in the infrared, in which case the minimum focus fell at 9,500 Å. In both cases the focal lengths at the D line at 5,890 Å were equal, and were assumed to be 100 units. The color curves for the two lenses are reproduced in Figure 86, from which it is evident that drastic changes may be necessary in a lens if it is to be achromatized in the near infrared instead of in the visible.

In ordinary photography, it is general practice to use a supplementary lens to change the effective focal length of the camera lens. The portrait attachment is an example of this. The use of auxiliary lenses is also common in astronomical photography when it is desired to change the achromatization of the main lens, designed for visual observation, so that it can be used for photography. Likewise it has been suggested that a supplementary lens could be employed in infrared photography to compensate for the difference in focus of the camera lens in the visual and infrared regions. Jasienski⁴⁶ proposed to do this by using a weak lens combined with the infrared filter, such as the Dukar and Lukor optically compensating filters, to shorten the infrared focus. Focusing is done visually without the filter, and the exposure is made with the filter in position. In commenting on the suggestion of Jasienski, Harting³⁷ considered that the use of the Schroeder chromatic plano-parallel plate (Rudolph hyperchromatic lens) might provide a solution. This is a lens of zero power, that is, having parallel sides, but compounded of a plano-convex and a concavo-plane lens having equal radii of curvature so that they can be cemented together centrally. The two components are made of glasses so chosen that their refractive indices

are equal for one part of the spectrum and different for another. By suitable design it is possible to make such a lens produce no change in focal length at one wavelength and a desired correction at another. Harting calculated one for wavelengths 5,890 and 8,500 Å.

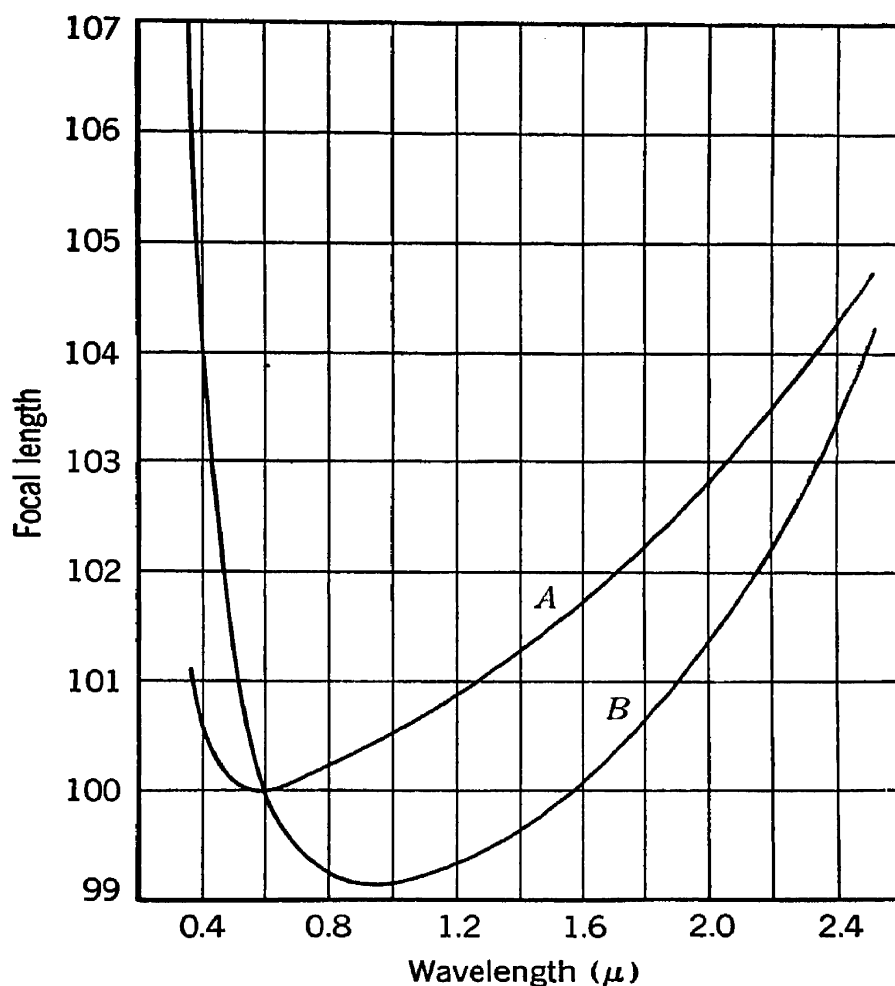


FIG. 86. Color curves for visual and photographic achromatism. The photographic lens *B* is achromatized for the infrared.

(From Kingslake and Conrady)

A concave mirror does not cause the separation of wavelengths produced by a simple lens. It was for this reason that Newton used a reflector instead of a lens in designing his telescope. It thus might appear that a mirror would offer a solution to the problem of focusing cameras for the infrared, and, in fact, objectives have been designed for this purpose, consisting of a single mirror, or a mirror-lens combination.⁴ So far they have not been used much for photography, although their application might well be seriously considered, particularly for telephotography

The Schmidt optics consisting of a mirror and correcting plate has been introduced in recent years for astronomy, television projection, and other purposes.

FILTERS

Filters for use in photography generally consist of thin layers of material which is transparent to certain regions of the spectrum and absorbs others. For example, a red filter, such as the Wratten no. 25, if placed in a beam of white light, absorbs the blue and green and allows only the red to pass; a green filter (Wratten no. 58) stops blue and red and transmits green; a blue filter (Wratten no. 47) absorbs green and red and passes blue; a yellow filter (Wratten K3) absorbs blue and transmits green and red. By proper selection of the materials of which filters are made, it is possible to absorb or transmit, within limitations, any desired region of the visible spectrum.

There are three ways in which filters are commonly prepared: (a) As solutions held in narrow glass cells with parallel sides, (b) in the form of thin gelatin or other plastic sheets containing dyes, (c) as sheets of colored glass. The gelatin film filters (b) are often cemented between thin glass sheets for protection. Liquid filters (a) are rarely used in photography owing to their bulk and inconvenience. They may be required in rare cases where special optical characteristics are desired which are not available in filters of other types. Gelatin (plain or cemented) and glass filters are almost exclusively used for photography. The gelatin types can be prepared in much greater variety than the glass filters, and they are also in general more reproducible.

According to the manner in which they absorb and transmit different regions of the spectrum, filters can be divided into three classes: (1) Those which absorb fully below a certain wavelength and transmit freely above it, (2) those which absorb strongly above a particular wavelength and transmit freely over a wide adjacent spectral range of shorter wavelength, (3) those which absorb strongly except in certain narrow regions of the spectrum. The filters of the first class commonly used by photographers are the yellow, orange, and red gelatin and glass filters. Those in the second class are not in common use for photography, while the third class includes the so-called monochromatic filters

and those used for isolating the blue and green. Filters employed in infrared photography are generally of the first kind, that is, those which absorb all wavelengths below a certain value. On some occasions it is desired to absorb the longer infrared, or parts of it, and filters of the second class would be required. Unfortunately, very few dyes are known which absorb the infra-

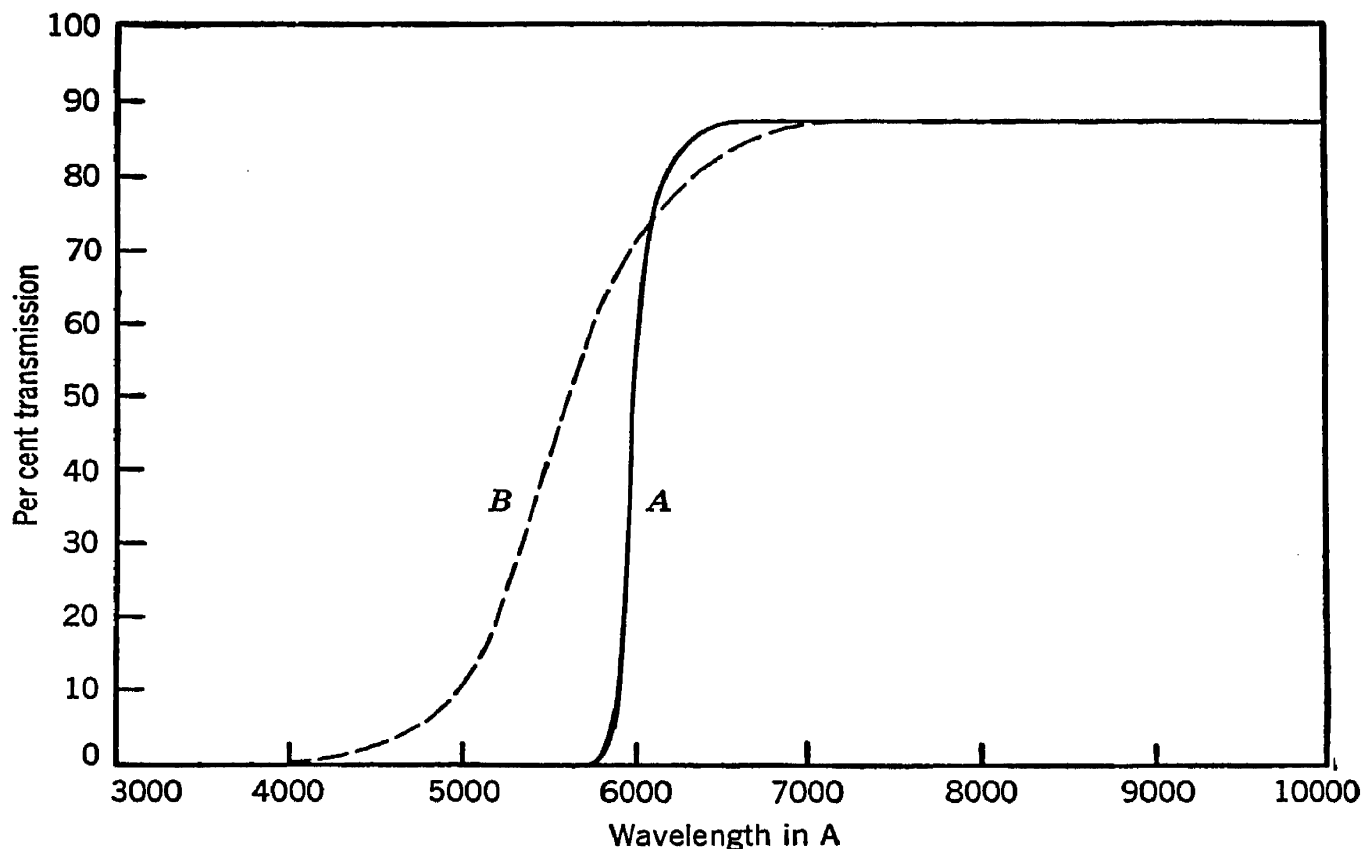


FIG. 87. Typical transmission curves of sharp cut (A) and gradual cut (B) filters.

red and transmit the visible freely, and so it is usually necessary for such purposes to resort to special glasses or to liquid filters. The infrared sensitizing dyes absorb in spectral regions closely allied to those in which they sensitize, and some of them have been proposed for use in filters. They are, however, often very unstable.

In designing filters, the manufacturer aims at securing the maximum transmission of the appropriate wavelengths, and the most effective elimination of the unwanted ones.^{24, 26, 30, 43, 73} In this connection, the terms "sharp cut" and "gradual cut" frequently are employed. Their significance may be illustrated by

reference to Figure 87, which shows typical spectrophotometric transmission curves of filters of these two types. The curves were obtained by plotting the percentage transmission of the filters against the corresponding wavelengths. This is common practice in describing the properties of filters and has been employed elsewhere in this book. An alternative method, which has some advantages, is to plot density instead of transmission (see p. 49). For the sake of uniformity, however, transmission values are used here.

Curve *A* represents a sharp-cut filter which is characterized by a rapid transition from absorption to transmission at about 6,000 Å. Curve *B* is for a gradual-cut filter, and the transition from complete absorption to maximum transmission occurs over a broad band of wavelengths. It should be observed that no filter transmits the incident light fully 100 per cent, because there is always some light lost by reflection at its two surfaces, even if there is negligible absorption by the filter material itself. In making filters, it is usually desired that the cut should be as sharp as possible, for the efficiency of a filter is determined by the most complete transmission of the wanted wavelengths and full absorption of those it is required to eliminate.

By proper selection of dyes, gelatin filters can be made having sharp cuts situated at very closely spaced intervals through the visible region. Since most dyes transmit freely in the infrared, no useful sharp-cut dyed-gelatin infrared-absorbing filters are available. A few dyes have some absorption in the infrared, but they give filters of the gradual-cut type. In glass filters, metallic oxides are added to the basic glass to give the necessary absorption (see p. 423). In their case also, sharp cuts can be obtained in the visible spectrum, but as the cut progresses into the infrared it becomes more gradual.

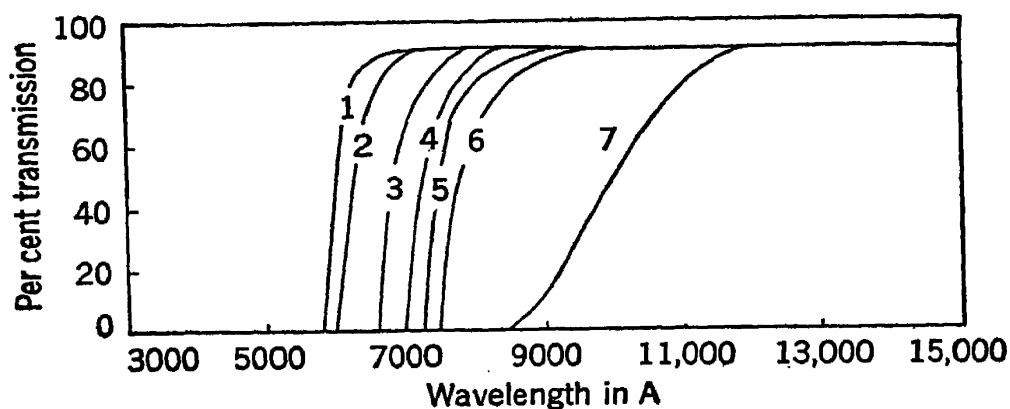
Infrared-sensitive plates and films respond in the blue and green as well as in the infrared. In order to confine the exposures to the infrared it is therefore necessary to absorb blue and green light. If it is desired to utilize the full range of spectral sensitivity of the photographic material in the infrared, the filter must absorb none of the effective long-wavelength radiation. Filters which possess both these characteristics are the orange and red gelatin film filters and glasses (see p. 422). Some infrared plates

and films are sensitive to wavelengths as short as 6,500 Å in the red. Clearly, a filter for use with them must have its cut at shorter wavelengths than this if the full sensitivity range is to be employed. If the exposure is to be confined to longer wavelengths, two courses are open. With a material sensitive over the range, say, from 6,500 Å into the infrared, a filter must be used having its cut at the minimum wavelength required. Such a filter will be deep red, or even opaque to visible light, transmitting only the infrared. The alternative method is to utilize a plate or film which is not sensitive at wavelengths shorter than the minimum to be used. In such a case, any filter can be used which has a cut lying between this wavelength and the longest wavelength to which the material is sensitive in the green. Many filters are available which have sharp cuts lying between wavelengths 6,000 and about 8,000 Å. A few other specially made filters cut at longer wavelengths. A list of some useful filters, with the positions of their cuts, is given in Table IV, p. 20. The transmission curves of some infrared-transmitting filters are reproduced in Figure 88.

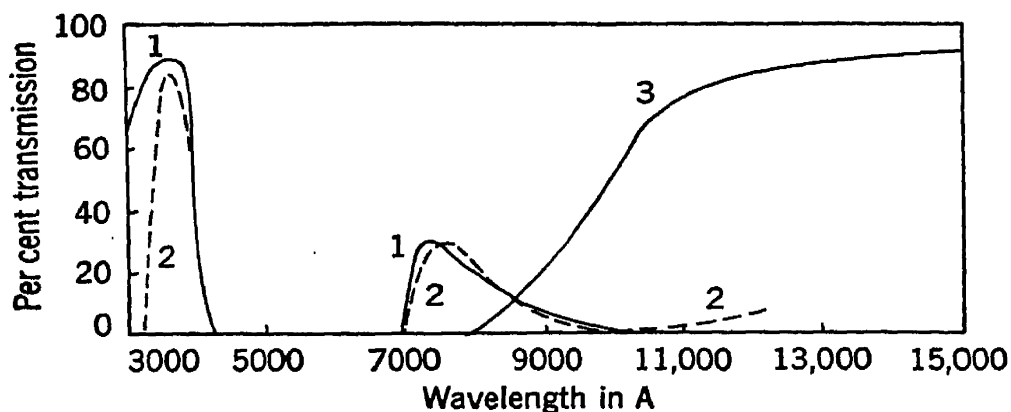
Filters of the second class, absorbing the infrared and transmitting in the visible, are sometimes used, although rarely in photography. They are generally made of glass and are all colored (see p. 423). They include the heat-absorbing glasses. The transmission curves of some of them are shown in Figure 89.

It is sometimes possible to find mixtures of dyes which can be used to make filters of the third class having narrow transmission bands. They can also be prepared by combining other filters, although higher efficiency can usually be achieved if the dyes are specially selected. In certain cases, particularly for the infrared, dyes cannot be found which will give narrow transmission bands, because none of them absorbs strongly on the long-wavelength side and transmits the shorter wavelength freely. In this event, therefore, it is customary to make combination filters, using a dyed gelatin or colored glass to give the cut on the short-wavelength edge, and water, solutions of salts, or special infrared-absorbing glasses to absorb beyond the transmission band.

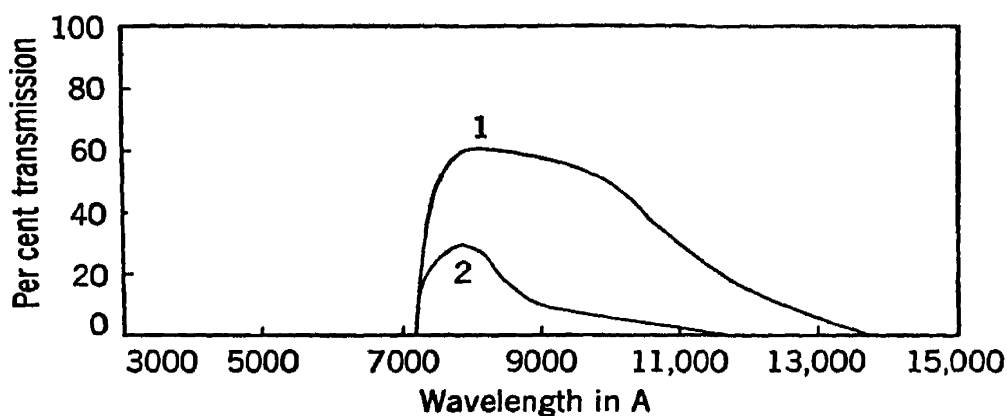
Water absorbs very strongly at a wavelength of 14,000 Å and is therefore used if it is necessary to confine the transmission of the combination filter to wavelengths shorter than this. A



A. Wratten light filters: 1, no. 25; 2, no. 29; 3, no. 89; 4, no. 88; 5, no. 88A; 6, no. 87; 7, special batch 5233.



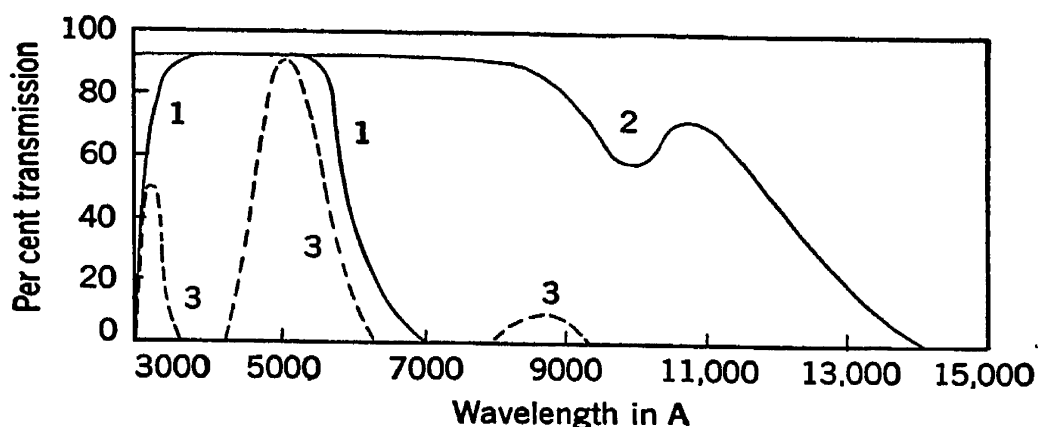
B. 1. Corning Red Purple Corex A glass, no. 986A, 0.5 cm thick.
2. Corning Violet Ultra glass, no. 586, 0.5 cm thick.
3. Corning Heat Transmitting glass, no. 254, 0.19 cm thick.



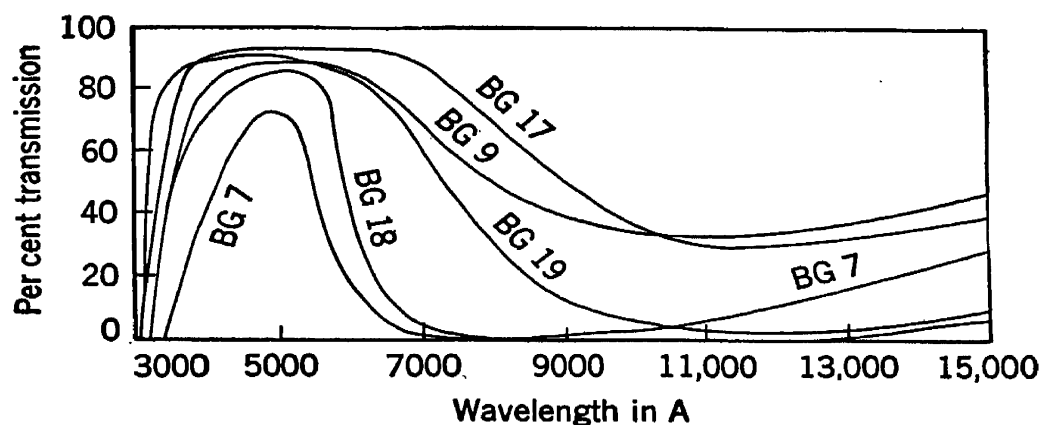
C. 1. Combination of Wratten filter no. 88A with a 2-cm layer of water.
2. Combination of Wratten filter no. 88A, a 2-cm layer of water, and 3.2 mm of Corning glass, G986A.

FIG. 88. Transmission curves of infrared-transmitting filters.

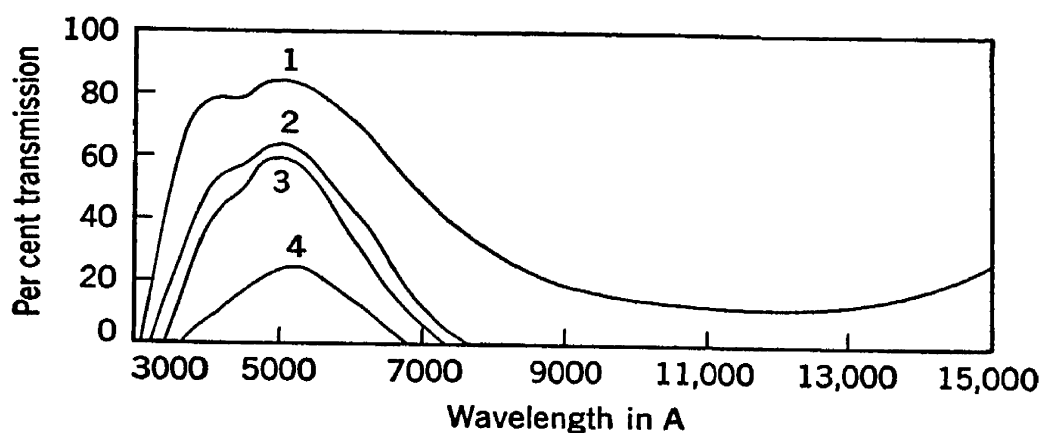
(From Eastman Kodak Co., Corning Glass Works, and L. A. Jones)



- A. 1. Copper sulphate ($\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$), 10 per cent solution in water, 1-cm layer.
 2. Water, 2-cm layer.
 3. Nickel sulphate ($\text{NiSO}_4 \cdot 7\text{H}_2\text{O}$), 50 per cent solution in water, 1-cm layer.



- B. Schott infrared-absorbing glasses, as numbered, 1.0 mm thick.



- C. 1. Solex heat-absorbing glass, 6.68 mm thick.
 2. Corning Light Shade Aklo glass, no. 396, 3.80 mm thick.
 3. Corning Medium Shade Aklo glass, no. 397, 3.80 mm thick.
 4. Corning Dark Shade Aklo glass, no. 398, 3.80 mm thick.

FIG. 89. Transmission curves of infrared-absorbing filters.

(From L. A. Jones, *Schott and Gen., Pittsburgh Plate Glass Co., and Corning Glass Works*)

solution of copper sulphate absorbs the short infrared very strongly. Figure 89A shows the absorption characteristics of water and of solutions of copper and nickel sulphates.⁴² The last-named has relatively narrow transmission bands, having maxima at 3,000, 5,300 and 8,600 Å. Used in conjunction with a deep red filter, nickel sulphate provides a narrow band in the infrared at about 8,600 Å, although the transmission is rather low. Jones⁴⁷ has worked out a number of filter combinations suitable for isolating relatively narrow spectral regions in the infrared. The transmission curves of two of them are given in Figure 88C. Data for other useful filters are collected in Table IV, in the section of this chapter treating of general materials, and in the publications listed at the end of the chapter.

Filters for isolating wavelength bands in the infrared for biological purposes which might be of interest for some photographic experiments have been described by Jones,^{47, 48} and Jones and Tuttle.⁴⁹

Pfund⁶⁶ has described an interesting group of filters consisting of solutions which transmit and absorb the infrared. Water has a pronounced transmission band at 10,500 Å, and the transmission of copper sulphate solution is quite apparent in this region, especially when an incandescent lamp is used. This difficulty may be minimized if a water solution of ferrous ammonium sulphate is used, which is very transparent in the visible region and absorbs strongly in the infrared, with a sharp cut at about 7,000 Å.

A saturated solution of iodine in carbon disulphide or carbon tetrachloride (the latter has lower volatility) absorbs visible light very strongly but is highly transparent to the infrared, the transmission curve showing a sharp cut at about 8,000 Å.⁶⁶

Pfund⁶⁶ drew attention to the transparency of solutions of vanadyl sulphate in the near infrared. They are transparent to blue light, and to some extent to green, absorb the red very strongly, and transmit very freely beyond about 9,000 Å. At about 14,000 Å they naturally absorb again, owing to the strong water absorption. If such a solution is combined with Corning Signal Red glass, which absorbs the blue and green, a filter is obtained through which it is said to be impossible to see the sun's disk, and yet which transmits the near infrared freely.

A layer of celluloid containing Milori (iron) Blue, transmits in the blue and absorbs out to about 10,000 Å, where it begins to transmit strongly. Copper butyl phthalate in carbon tetrachloride transmits in the blue and also in the infrared beyond 10,500 Å.⁶⁰

So-called "neutral-density filters" are often employed to reduce the intensity of visible light. They are designed to have sensibly equal densities at all wavelengths in the visible. Some of them are made of dyes, however, and are very transparent in the infrared. In their case, the density values which apply to the visible spectrum would not necessarily have any significance in the infrared. Some neutral-density filters contain carbon black which is opaque to the infrared, and they can be used to absorb in this region. Usually, however, a dye is added to neutralize the yellowish color of a carbon-black filter, so that the densities which are measured by visible light will not apply accurately in the infrared; caution should be observed when such filters are used.⁶¹ Particularly misleading results may be secured if a neutral-density step wedge* is employed for measuring the speeds of infrared-sensitive plates and films. It will be satisfactory only if it has uniform transmission through the region of sensitivity of the material and if it has been specially calibrated for radiation of this wavelength.

A filter forms part of the optical system of the camera, and it should be used in such a manner that it introduces no distortions. If it is in the form of gelatin film, the filter must be stored and handled so that it does not become dirty or finger-marked, because it is not possible to clean it. If it is cemented in glass the definition may be spoiled if the glass is not of good optical quality. Cemented filters must be treated with the care accorded to lenses. They should not be permitted to become damp or dirty, they should not be strained by pressure, and they should be kept cool and in the dark when not in use.

THE CHRISTIANSEN AND POWDER FILTERS

A type of filter concerning which a large number of papers have been published is known as the Christiansen filter, from the

* An exposure modulator consisting of a series of areas arranged in decreasing order of transmission.

name of the man who first described in 1884 the effect on which it depends. The filter produces comparatively monochromatic beams of light having a high transmission at the wavelength of maximum transmission.^{3, 7, 60} It consists of a finely divided transparent crystalline powder, suspended in a transparent medium having a refractive index different in general from that of the powder. If the refractive indices of powder and medium are equal at some particular wavelength, this wavelength will be transmitted, while others will be scattered. If the wavelength of equal indices is in the visible, the light transmitted by the filter has a color corresponding to it. The image directly transmitted is surrounded by a scattered haze of complementary color. By appropriate selection of the materials of the filter and the temperature, the wavelength transmitted unscattered may be located in any part of the spectrum from the ultraviolet to the infrared. The wavelength transmitted by a Christiansen filter is dependent on the temperature, since the refractive indices of the liquid and powder will vary unequally with temperature. In use the filters must, therefore, be thermostatically controlled.

A number of investigators have studied the transmission properties of thin layers of powdered materials in the infrared.^{2, 3, 65, 68} In general the surrounding medium is air, and the transmission depends on the sizes and distribution of sizes of the particles, and the thickness and uniformity of the layer. Diffuse reflection and scattering occur, depending on the relation between the particle size and the wavelength, and it seems also that the Christiansen effect involving refraction comes into play. Powder filters have been prepared to have transmission limits at various wavelengths in the infrared, usually beyond the photographic limit. According to Plummer,⁶⁸ it is difficult to give specific directions for making powder filters to eliminate wavelengths below any desired point. The powder material should be highly transparent and the powders should be prepared in groups whose average particle size varies between one half and one eighth of the wavelength at which it is desired that the transmission should begin. The best thickness and particle size for particular needs must then be selected by trial and error.

POLARIZING SCREENS

In 1935 sheets of polarizing material were made available by the Polaroid Corporation and sold by the Eastman Kodak Company as Pola-screens and by Polaroid as Polaroid. They consisted originally of a plastic sheet containing minute crystals of birefringent material, such as herapathite, oriented by extrusion or other means to render their axes parallel. The present materials consist of a polyvinyl alcohol sheet the polarizing properties of which have been achieved by producing a parallel alignment of the long molecules of the material itself.⁶⁹ The sheets are usually mounted in cellulose acetate sheets for use. They are very efficient polarizers for visible light, and are used in photography for reducing reflections, in stereoscopy, in outdoor optical instruments for reducing glare, in scientific instruments, and in other important ways. A polarizing filter put out as the Herotar by Zeiss-Ikon in 1936 consisted of a single thin crystal of herapathite on glass. Its properties were similar to the early Pola-screen, but it was limited in size.

Pola-screens available at the time of writing (1945) are of no value for infrared photography, because their polarizing efficiency in the infrared is very low. They are, in fact, designed to have a high degree of transparency in the infrared.

SAFELIGHTS FOR THE INFRARED

A safelight is a filter used in a lamphouse to provide photographically safe illumination in a darkroom. The light from a safelight should be of such spectral quality and intensity that it does not fog films handled by it, and yet the illumination provided by it should be as high as possible consistent with safe handling of the material. The conditions are clearly interdependent.

Safelight glasses are selected to transmit light of wavelengths to which the films are not appreciably sensitive, or, in the case of panchromatic materials which respond to all visible wavelengths, the light is selected to have a low intensity in the region of the spectrum to which the eye has its maximum sensitivity, that is, in the green. Infrared films usually have low sensitivity in the green, and an infrared safelight will therefore transmit light of this color. It will absorb the shorter-wavelength blue

and violet and the red and infrared. Safelights for use with panchromatic films are green, but they are also quite transparent in the invisible infrared and thus are entirely unsuited for use with infrared-sensitive films.

A typical safelight for infrared films and plates is the Wratten Series VII safelight, which is green in color and which transmits no infrared to which the common materials are sensitive. It consists of a combination of glass coated with dyes having the proper transmission in the visible, and an infrared-absorbing glass. A combination of this type which has been proposed is a glass coated with gelatin containing the dye Naphthol Green, and a yellow dye or glass to absorb the blue-green which is transmitted by the Naphthol Green, together with an infrared-absorbing glass which transmits the green.

Materials which absorb the infrared effectively and yet transmit visible green well are few in number. In addition to having suitable spectral transmission, they must be stable to the heat and light from the lamp with which they are used. A ten per cent solution of copper sulphate in a layer 1 cm thick possesses the desired characteristics. Leiber⁵⁸ described a safelight containing such a solution in conjunction with potassium dichromate to absorb the violet and blue. A solution is very inconvenient to use, however, and many attempts have been described to incorporate complex copper salts in gelatin to replace the copper sulphate solution. Some heat-absorbing glasses, however, are very satisfactory and are simpler to use than gelatin-coated glass.

Iron compounds possess strong absorption in the infrared, and suspensions of Prussian Blue in gelatin have been proposed for coating on glass to provide the infrared-absorbing member of safelights. Prussian Blue, however, is unstable and thus is not satisfactory. Kusminsky and Kusmenkoy⁵⁵ recommended a safelight consisting of Prussian Blue in gelatin—and excused its use on the grounds that its bleaching by light is reversed in the dark—combined with a layer containing Naphthol Green and nitrosodimethylaniline or Chrysoidine.

Dyes which are used for sensitizing emulsions absorb light approximately in the region of the spectrum to which they

sensitize, and it might appear that they could be used in safelights.^{41, 42} Unfortunately, most of them have low absorbing power and are unstable. Kryptocyanine has been suggested, but it transmits beyond about 8,000 Å, and so the common infrared materials cannot be used with it. According to a patent of I. G. Farbenindustrie,⁴² certain infrared-sensitizing dyes are unstable in alcohol or water, but are stable in gelatin layers and can be used to absorb infrared. Allocyanine (Neocyanine) and di- and tricarboyanines containing thiazole, selenazole, or quinoline rings are suitable (see Chapter V). Layers containing these dyes are green and should be used in conjunction with yellow or orange filters to absorb the violet, blue, and blue-green.

Safelights are normally provided with a low-wattage tungsten-filament lamp. A satisfactory safelight clearly could be made from a lamp which had a bright emission in the safe spectral region and no emission in the region it was desired to absorb. No such ideal lamp is available, but some gaseous-discharge lamps have been adapted. For instance, Bertling⁶ considered sodium, thallium, and mercury lamps to be satisfactory, if they were provided with filters to absorb the undesirable spectral lines. The thallium lamp appeared to be the most useful, since it has no emission in the near infrared to which the common infrared films are sensitive, and yet it has a strong emission line in the green at 5,350 Å. It was recommended for use in conjunction with 1 mm of Schott BG7 and 0.5 to 1 mm of Schott OG1 glasses to absorb the lines in the ultraviolet, blue, and red, which are rather weak.

In order to make infrared safelights from sodium and mercury lamps, Bertling⁶ recommended combining the lamps with a 30-mm layer of copper sulphate solution (1:17.5) and 1 mm of Schott glass OG1. Agfa recommended for infrared photography the use of an ordinary neon glow lamp in conjunction with the Agfa safelight no. 114.

The manufacturers of safelights invariably give instructions for their proper use to ensure safety in handling the materials for which they are intended. For instance, for the Kodak films and plates of normal infrared sensitivity, it is specified that the Wratten Series VII safelight should be used with a 10-watt lamp

at a minimum distance of 3 ft from the material to be handled or developed.

The safety of a safelight for infrared cannot be judged by its visual appearance nor by its behavior with panchromatic films. If there is any doubt as to its safety, it should be tested. A low-wattage lamp should be used, certainly not rated at higher than 25 watts, and the lamphouse should be suspended 3 ft above the bench in the darkroom and pointing directly down at it. The film should be placed emulsion side up directly under the lamp and covered with a black card opaque to infrared. After the safelight is switched on, the film should be exposed 1 in. at a time by moving the card across it in steps at 10-second intervals. Alternatively, the reverse procedure may be used, especially if a wider range of exposures is desired. The whole film is uncovered for 10 seconds, the 1 in. is covered, and the rest is exposed for 10 seconds more. The second inch is then covered and the rest exposed for an additional 20 seconds, and so on, the exposure being doubled at each step. After exposure, the film is developed under the conditions which will be employed in its use, and the step noted which is just visible. The exposure corresponding to this can be taken as the maximum safe exposure time for the safelight under the conditions of test.

TRANSMISSION OF VARIOUS COMMON MATERIALS IN THE INFRARED

The literature on the transmission of pure substances and solutions in the infrared is very extensive. In recent years particular study has been made of the properties of organic compounds with a view to elucidating their molecular structure. For information on the results of these and other investigations of chemical compounds, the reader should refer to the chemical and physical literature and to the tables of chemical and physical constants. There are many occasions when the photographer is interested in the behavior of common materials in the infrared. The data given in the following pages relate to a number of these which are not discussed in the earlier sections of this chapter or in Chapter VIII.

TABLE XXVIII
AIR, MOIST AND DRY ⁷⁶

λ	3,600	3,840	4,130	4,520	5,030	5,350	5,740	6,240	6,530	7,200	9,860	17,400
a	(0.660)	0.713	0.783	0.840	0.885	0.898	0.905	0.929	0.938	0.970	0.986	0.990
a_w	0.950	0.960	0.965	0.967	0.977	0.980	0.974	0.978	0.985	0.988	0.990	0.990

λ = wavelength in A.

a = transmission by dry air above Mount Wilson (altitude = 1,730 m, barometer 620 mm) for a body in the zenith.

a_w = correction factor due to such a quantity of water vapor in the air that if condensed it would form a layer 1 cm thick.

NATURAL AND SYNTHETIC ORGANIC MATERIALS ^{13, 17, 77}

ANIMAL PROTEIN. Chitin is very transparent in the near infrared to about 25,000 A. Other animal proteins in general exhibit the same behavior. Egg albumin is transparent in the visible and infrared to 25,000 A. Gelatin is quite transparent to about 30,000 A.

CELLULOSE. Natural cellulose exhibits high transmission in the near infrared; the first strong absorption bands appear at about 30,000 A. Cellophane, a regenerated cellulose manufactured in the form of thin sheets for wrapping and other purposes, is very transparent out to about 30,000 A.

RUBBER. Rubber and related hydrocarbons show a high transmission in the near infrared, the first strong absorption band occurring beyond 30,000 A. With aging the infrared-absorption spectrum is changed, but no absorption band enters the photographic region.

SHELLAC. This is transparent, showing its first strong absorption band at 29,000 A.

SYNTHETIC RESINS. Vinyl and Glyptal resins are transparent to nearly 30,000 A.

SOLUTIONS OF INORGANIC SALTS ^{13, 45, 66}

CHROME ALUM. Transparent from about 7,000 to 15,000 A in a 1-cm layer of 10 per cent solution.

CHROMIUM SULPHATE. There is an absorption band from about 7,500 to 20,000 Å in a 1-cm layer of 1 per cent solution.

COPPER SALTS. In general, these show strong absorption in the near infrared. See Figure 89 and p. 423.

Cupric chloride, $\text{CuCl}_2 \cdot 2\text{H}_2\text{O}$. A 2-cm layer of 5 per cent solution absorbs practically beyond about 6,500 Å.

Copper potassium chloride, $\text{CuCl}_2 \cdot 2\text{KCl} \cdot 2\text{H}_2\text{O}$. Resembles cupric chloride.

Copper sulphate, $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$. See p. 423 and Figure 89.

NICKEL SALTS. These show absorption in the infrared, but there is a strong narrow transmission band at about 8,600 Å. See p. 423. Nickel salts are not so satisfactory as cupric chloride for absorbing the infrared.

POTASSIUM DICHROMATE, $\text{K}_2\text{Cr}_2\text{O}_7$. Transparent in the infrared.

AMMONIUM IRON ALUM, $(\text{NH}_4)_2 \cdot \text{Fe}(\text{SO}_4)_7$. Strong transmission bands at 6,500 and 10,500 Å, and a large absorption band at 8,500 Å.

FERROUS AMMONIUM SULFATE, $\text{Fe}(\text{NH}_4)_2(\text{SO}_4)_2$. Absorbs strongly beyond about 7,000 Å. See p. 424.

IODINE in carbon tetrachloride or carbon disulphide. Highly transparent in the infrared beyond about 8,000 Å, strongly absorbing in the visible.

VANADYL SULPHATE, $(\text{VO})(\text{SO}_4)$. Transmits very freely beyond about 9,000 Å. See p. 424.

SENSITIZING DYES

Absorption bands in approximately the following positions:

Discyanine.....	5,800 and 6,600 Å
Kryptocyanine.....	7,050 Å
Neocyanine.....	7,750 Å
Xenocyanine.....	8,300 and 9,300 Å

See also Chapter V, and references.^{41, 42}

MINERALS

According to the data obtained by Königsberger⁵⁴ for doubly refracting crystals, the following minerals are transparent to wavelengths beyond 20,000 Å: Amethyst, aragonite, barytes, cerussite, muscovite, celestite, and clear quartz. The following

show interesting absorption characteristics in the near infrared:

GYP SUM. Absorption band at 15,000 Å, and full absorption beyond 20,000 Å.

MICA. Muscovite has a high transmission increasing to a maximum at 20,000 Å, with moderate absorption from 22,000 to 32,000 Å.

Biotite (black mica) has a very strong absorption in the visible and to about 10,000 Å; the transmission then increases to a high value at 21,000 Å.

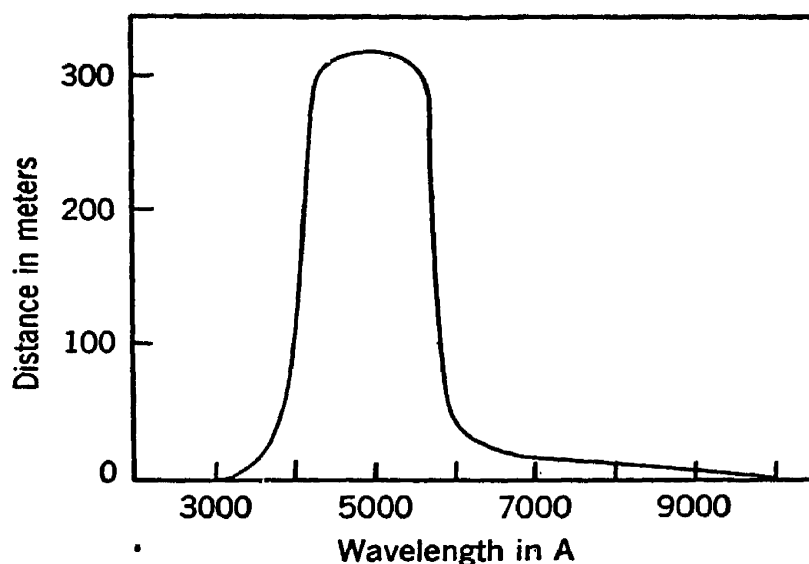


FIG. 90. Penetration of light in sea water.

The curve shows the distances which light of various wavelengths penetrates to be reduced to 1/1,000 of its original intensity.

(From Hulburt)

QUARTZ. Clear quartz is transparent to 36,000 Å, whereas the smoky variety absorbs in the visible; its transmission then increases to a maximum at 11,000 Å and beyond.

In most doubly refracting crystals the absorption of the extraordinary ray is somewhat different from that of the ordinary ray, but the absorption curves generally have roughly similar shapes.

See also Coblentz.^{11, 13, 16}

THIN METALLIC LAYERS

Goos measured the transmission and reflectivity of thin layers of gold³⁵ and silver³⁴ in the ultraviolet, visible, and infrared, for a wide range of thicknesses. The original papers should be

consulted for full details of the results. In the case of both metals, for a wavelength of 10,500 Å, transmission and reflectivity were equal and about 30 per cent for a layer 9 $m\mu$ thick.

See also Coblentz, Emerson, and Long.²⁰

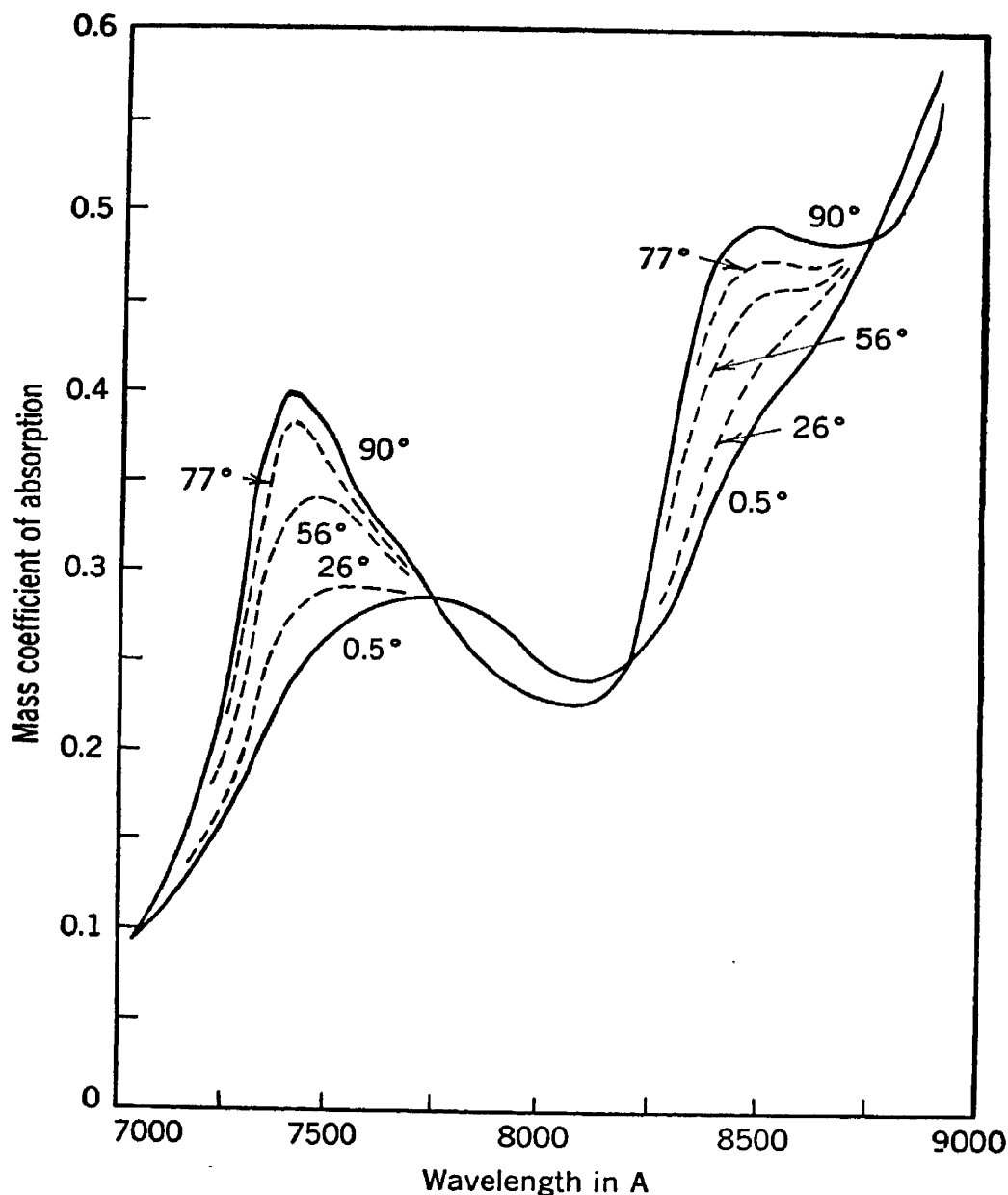


FIG. 91. Infrared-absorption curve of water as a function of temperature.
(From Collins)

WATER

See pp. 220 and 423.

SEA WATER. The curve in Figure 90, due to Hulburt, shows the distances which light of various wavelengths penetrates into the ocean to be reduced to 1/1,000 of its original intensity.

A bibliography of the transmission characteristics of water has been issued by the National Research Council, Ottawa, Canada.⁷² See also Darby, Johnson, and Barnes,²⁵ and Clarke and James.^{9a}

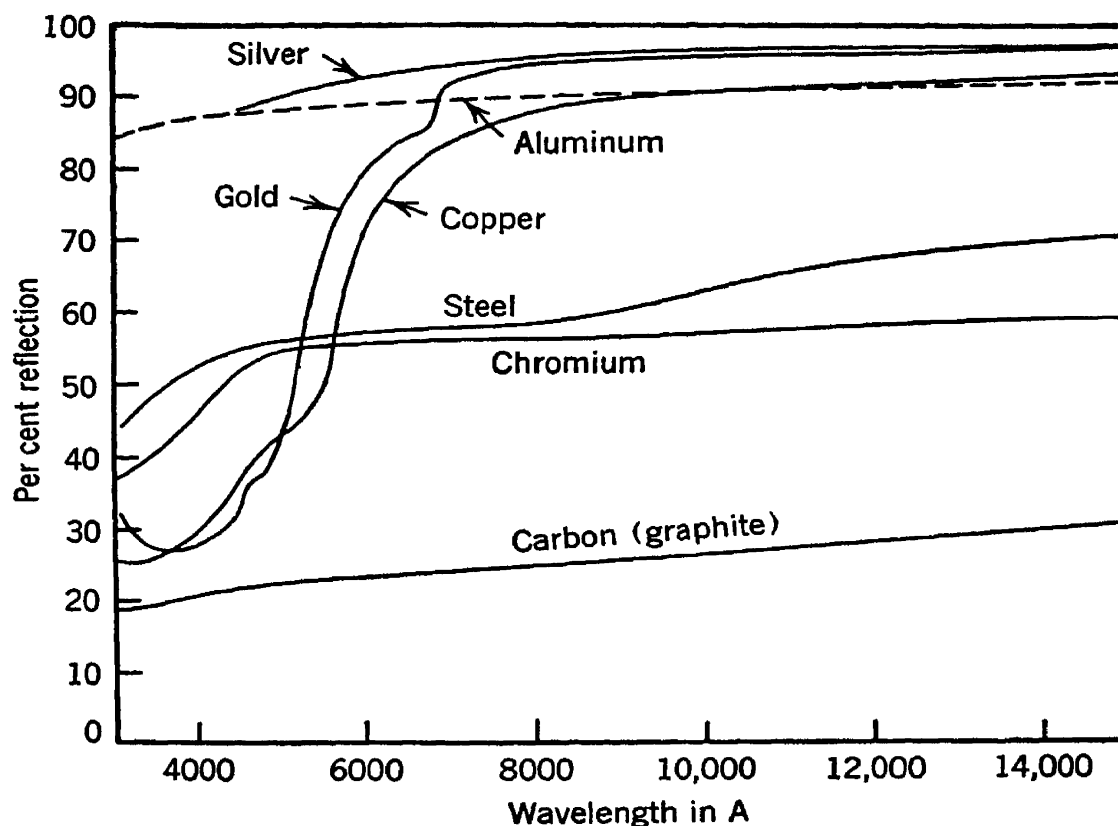


FIG. 92. Spectral reflectivities of metals and carbon.

(Based on Coblentz, Edwards, and International Critical Tables)

Figure 91 shows infrared-absorption curves of water for a range of temperatures published by Collins.²³ In the curves, the "mass coefficient of absorption" is used, because it is a quantity comparable at various temperatures. It is

$$k = (1/t\rho) \log (d_0/d)$$

where t is the thickness of the water layer, ρ is the density of the water at the temperature for which d is the deflection of the measuring galvanometer when the cell is in the path, and d_0 is the deflection when nothing is in the path.

REFLECTING POWERS OF MATERIALS IN THE INFRARED

BUILDING MATERIALS. Data from the paper of Beckett,⁵ giving diffuse reflecting powers, are presented in Table XXIX.

TABLE XXIX
REFLECTING POWERS OF BUILDING MATERIALS IN THE INFRARED

<i>Filter, λ in \AA</i>	<i>I</i> 17,800	<i>II</i> 8,400	<i>III</i> 6,100	<i>IV</i> 5,000	<i>Gold Film</i>	<i>Com- puted</i>
Magnesium carbonate	0.63	0.99	0.98	0.96	0.96	....
<i>Clay Tiles</i>						
Dutch, light red	0.68	0.66	0.56	0.21	0.57	0.52
Machine-made, red	0.72	0.42	0.34	0.11	0.38	0.38
Machine-made, red	0.55	0.38	0.31	0.11	0.34	0.33
Machine-made, lighter red	0.52	0.40	0.32	0.13	0.34	0.33
Machine-made, dark purple	0.22	0.22	0.19	0.13	0.19	0.18
Handmade, red	0.60	0.47	0.37	0.12	0.40	0.39
Handmade, red-brown	0.55	0.33	0.28	0.13	0.31	0.31
<i>Concrete Tiles</i>						
Uncolored	0.37	0.38	0.36	0.27	0.35	0.33
Black	0.06	0.09	0.09	0.09	0.09	0.08
<i>Slates</i>						
Dark grey, smooth	0.09	0.11	0.11	0.11	0.11	0.10
Greenish grey, rough	0.16	0.11	0.12	0.13	0.12	0.13
Blue-grey	0.20	0.16	0.13	0.12	0.13	0.15
Silver-grey (Norwegian)	0.22	0.21	0.21	0.19	0.21	0.20
<i>Other Roofing Materials</i>						
Asbestos-cement, white	0.35	0.42	0.41	0.36	0.41	0.39
Asbestos-cement, red	0.33	0.33	0.29	0.14	0.31	0.26
Galvanized iron, new	0.58	0.30	0.34	0.34	0.35	0.35
Galvanized iron, very dirty	0.10	0.09	0.09	0.09	0.09	0.09
Galvanized iron, whitewashed	0.63	0.79	0.79	0.76	0.78	0.74
Bituminous felt	0.10	0.12	0.11	0.11	0.12	0.11
Aluminized felt	0.67	0.60	0.61	0.57	0.62	0.60
Weathered asphalt	0.12	0.12	0.11	0.09	0.11	0.11
Roofing lead, old	0.46	0.20	0.19	0.15	0.21	0.23
<i>Bricks</i>						
Gault, cream	0.74	0.69	0.64	0.43	0.64	0.61
Stock, light fawn	0.56	0.47	0.38	0.19	0.44	0.39
Fletton, light portion	0.67	0.61	0.57	0.35	0.58	0.52
Fletton, dark portion	0.54	0.46	0.37	0.15	0.41	0.37
Wire cut, red	0.56	0.48	0.41	0.15	0.44	0.39
Sand-lime, red	0.41	0.37	0.30	0.11	0.32	0.30
Mottled purple	0.33	0.26	0.22	0.15	0.23	0.23
Stafford, blue	0.21	0.12	0.11	0.08	0.11	0.12
Lime clay (French)	0.57	0.63	0.52	0.29	0.54	0.49

Four filters were used, transmitting fairly narrow bands equally spaced on a frequency scale through the solar spectrum.

Filter I, 17,800 \AA ; Chance blue-green contrast filter no. 6, 3.3 mm thick, with Chance orange contrast filter no. 4, 2.7 mm thick.

Filter II, 8,400 \AA ; 2 cm water, with Chance orange contrast filter no. 4, and cobalt blue glass, 1.8 mm thick.

Filter III, 6,100 \AA ; 1 cm potassium dichromate solution (72 grams per liter) and 1 cm copper sulphate solution (57 grams hydrated salt per liter).

Filter IV, 5,000 \AA ; 2 cm saturated copper sulphate solution at 14.2° C.

Gold film, radiation from a Pointolite through a thin gold film resembles that of sunlight in range and distribution and enables the reflecting power for total sunlight to be determined approximately in a single reading.

Computed values are based on the energy curve of the sun at 60° elevation.

METALS. Some data on the reflectivity of metals are presented in Table XXX.

METALS AND CARBON. The following curves were drawn from data derived from the "International Critical Tables," Coblentz,^{11, 12} and Edwards³¹ (Figure 92). The curves were obtained for the massive metals, with the exception of gold, the

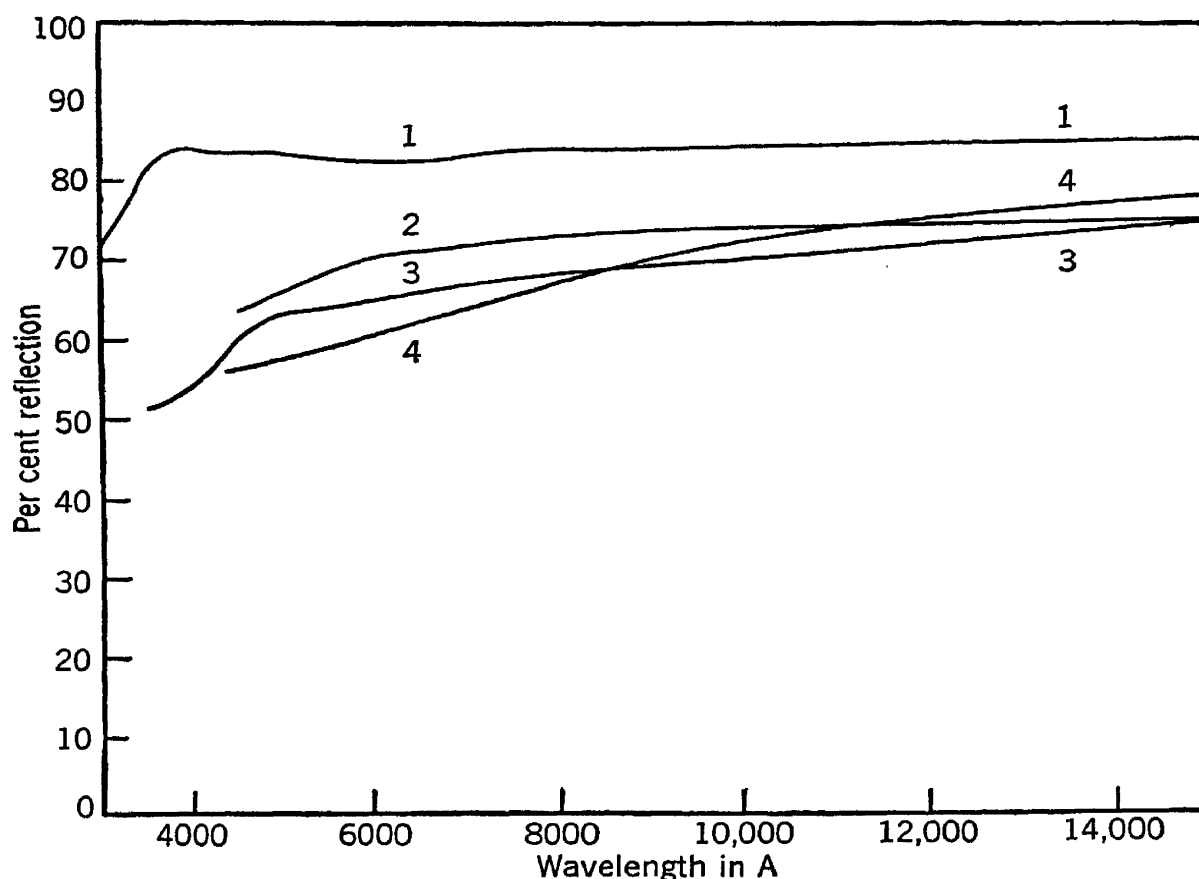


FIG. 93. Spectral reflectivities of alloys.

(Based on data in *International Critical Tables* and Coblentz)

values for which apply to an opaque film electrolytically deposited.

ALLOYS. Figure 93 shows the reflectivity of the following alloys:

1. Mach's mirror amalgam.
2. Stellite.
3. Speculum metal.
4. Monel metal.

The data were obtained from the "International Critical Tables." See also Coblentz and others.^{15, 19, 21, 79}

TABLE XXX

METALS

λ in μ	3,570	3,850	4,200	4,500	5,000	5,500	6,000	6,500	7,000	8,000	10,000	15,000
Nickel												
Electrolytic	48.8	49.6	56.6	59.4	60.8	62.6	64.9	66.6	68.8	69.6	72.0	78.6
Copper												
Commercial, pure	27.3	28.6	32.7	37.0	43.7	47.7	71.8	80.0	83.1	88.6	90.1	93.8
Speculum metal												
68.2 Cu + 31.8 Sn	51.0	53.1	56.4	60.0	63.2	64.0	64.3	65.4	66.8	...	70.5	75.0
Platinum												
Electrolytic	43.4	45.4	51.8	54.7	58.4	61.1	64.2	66.5	69.0	70.3	72.9	77.7
Gold												
Electrolytic	27.9	27.1	29.3	33.1	47.0	74.0	84.4	88.9	92.3	94.9	...	97.3
Silver												
Chemically deposited	74.5	81.4	86.6	90.5	91.3	92.7	92.6	94.7	95.4	96.8	97.0	98.2
Steel												
Untempered	45.0	47.8	51.9	54.4	54.8	54.9	55.4	56.4	57.6	58.0	63.1	70.8

Based on "Smithsonian Physical Tables," 8th ed., 1933, in turn based upon the work of Hagen and Rubens, *Ann. Physik*, 1900 (1), 352; 1902 (8), 1: 1903 (11), 873; and taken partly from Landolt-Börnstein-Meyerhoffer's "Physikalisch-Chemische Tabellen." See also Coblentz and others.^{11, 12, 15, 19, 21, 79}

λ = wavelength in μ . The numbers give the percentages of incident radiation reflected, for perpendicular incidence and reflection.

TABLE XXXI

DIFFUSE REFLECTING POWERS OF VARIOUS MATERIALS

<i>Material</i>	<i>Reflecting Power (Per Cent) for Wavelength of</i>		
	<i>5,400 Å</i>	<i>6,000 Å</i>	<i>9,500 Å</i>
Silver	93.2	89.9	93.4
Aluminium	....	68.5	....
Lamp Black paint	....	3.10	3.38
Lamp Black paint, other samples	....	2.94–3.72	....
Lamp Black paint, paraffin candle	....	....	0.97
Lamp Black paint, rosin	....	....	1.26
Lamp Black paint, sperm candle	....	....	0.91–1.25
Lamp Black paint, camphor	....	....	1.30–1.36
Lamp Black paint, camphor paint	....	....	2.80
Lamp Black paint, acetylene	....	....	0.42–0.82
Lamp Black paint, acetylene, cold deposit	....	....	0.86
Lamp Black paint, acetylene, no air	....	....	1.33
Platinum Black, chemically precipitated	....	2.01	2.92
			2.43
Platinum Black, electrolytic	....	....	0.85–1.22
Pigments	....	....	3.92
Cobalt oxide, Co_2O_3	....	3.02	4.04
			2.49
Copper oxide, CuO}	....	....	23.5
Chromium oxide, Cr_2O_3	24.1	27.0	44.6
Red iron oxide, Fe_2O_3	....	26.3	41.0
Aluminium oxide, Al_2O_3	....	84.1	87.7
Zinc oxide, ZnO}	....	82.2	86.4
Zirconium oxide, ZrO_2	82.2	85.8	84.1
Lead carbonate, PbCO_3	....	86.8	90.8
		89.9	92.8
			94.5
Magnesium carbonate, MgCO_3	....	85.2	89.4
Paints			
White lead, no. 103	....	76.2	79.3
Zinc oxide, no. 104	....	68.1	72.1

PAINTS AND PIGMENTS. The infrared characteristics of a variety of paints and pigments are also described in Chapters VIII, XII, and XIII.

VARIOUS MATERIALS. Diffuse reflecting powers of various materials obtained by Coblentz¹⁰ are shown in Table XXXI.

TABLE XXXII

SNOW, SAND, ETC.

Wavelength in μ	Maine Sand	Florida Sand	Crushed Quartz	Snow	Plaster of Paris	White Paper	Sodium Carbon- ate	Sodium Chloride	White Cotton Cloth
3,000–4,000	8	15	40	35	40	8	14	38	36
4,000–8,000	25	40	50	40	53	30	28	49	42
8,000–26,000	33	50	53	15	60	30	35	54	40
26,000–70,000	31	30	28	18	63	15	18	55	20
70,000	48	..	..	26	..	..	..	..	..

These reflectivity data were published by Hulburt:⁴⁰

Diffuse reflecting powers in relative units.

Maine sand, yellow-white, made up of grains of many colors from sea-shore.

Florida sand, very white, containing quartz with some black specks, from two miles inland from sea.

Crushed quartz, made by grinding clear optical quartz in mortar.

Snow, untouched surface, freshly fallen.

Plaster of Paris, in powder form.

Paper, very slightly yellowish.

Sodium carbonate, anhydrous.

White cotton cloth, old cotton handkerchief, freshly washed and ironed.

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Appendix I

INFRARED MATERIALS AVAILABLE COMMERCIALY

The following list includes all those infrared-sensitive materials known to the author to be on the market in November 1945. All of them are sensitive in the violet and blue. The data given relate to their approximate sensitivity range in the infrared, and the position of maximum sensitivity in the infrared if it can be defined.

<i>Manufacturer and Name of Material</i>	<i>Sensitivity Range in A</i>	<i>Sensitivity Maximum in A</i>
Eastman Kodak Co.		
Kodak Infrared Sheet Film	6,800–8,600	8,300
Kodak Infrared Film (Miniature and Roll)	6,800–8,600	8,300
Kodak Aerographic Infrared Film (Reconnaissance) *	6,800–8,600	8,300
Eastman Infrared Negative Film (35 mm)	6,800–8,600	8,300
Kodak Infrared-Sensitive Plates	6,800–8,600	8,300
Eastman Spectroscopic Plates (see Figure 20, pp. 88, 89)		
Eight classes of sensitizing covering spectral regions out to 12,000 A are available in up to five basic emulsion types.		
Ilford, Ltd., England		
Ilford Infra-red Process Plates	6,500–8,500	8,100
Kodak, Ltd., England		
Kodak I.R.E.R. Extra Rapid Infra-red Plate	6,800–8,600	8,300
Kodak Scientific Plates		

A series of infrared-sensitive plates for scientific purposes corresponding in general to the Eastman Spectroscopic Plates

Anseo, DuPont, and Ilford have stated that they have temporarily withdrawn their infrared products from the market. It is understood that during the war the German Agfa company made infrared plates and films and special infrared plates for scientific purposes, but presumably they will no longer be available. In some Russian articles, mention has been made of Russian infrared materials, but no details are available.

* Earlier called Eastman Infrared Aero Film.

Appendix II

WEIGHTS AND MEASURES—CONVERSION TABLES

In photographic practice solids are weighed and liquids are measured either by the avoirdupois or the metric system.

The following tables of weights and measures give all the equivalent values required for converting photographic formulas.

AVOIRDUPOIS TO METRIC WEIGHT

<i>Pounds</i>	<i>Ounces</i>	<i>Grains</i>	<i>Grams</i>	<i>Kilograms</i>
1	16	7,000	453.6	0.4536
0.0625	1	437.5	28.35	0.02835
....	....	1	0.0648	....
....	0.03527	15.43	1	0.001
2.205	35.27	15,430	1,000	1

BRITISH IMPERIAL LIQUID TO METRIC MEASURE

<i>Gallons</i>	<i>Quarts</i>	<i>Ounces (Fluid)</i>	<i>Drachms (Fluid)</i>	<i>Milliliters *</i>	<i>Liters</i>
1	4	160	1,280	4,546	4.546
0.25	1	40	320	1,136	1.136
....	....	1	8	28.41	0.02841
....	0.003125	0.125	1 (60 min)	3.551	0.003551
....	....	0.03520	0.2816	1	0.001
0.2200	0.8800	35.20	281.6	1,000	1

U. S. LIQUID TO METRIC MEASURE

<i>Gallons</i>	<i>Quarts</i>	<i>Ounces (Fluid)</i>	<i>Drachms (Fluid)</i>	<i>Milliliters *</i>	<i>Liters</i>
1	4	128	1,024	3,785	3.785
0.25	1	32	256	946.3	0.9463
....	....	1	8	29.57	0.02957
....	....	0.125	1 (60 min)	3.697	0.003697
....	....	0.03381	0.2705	1	0.001
0.2642	1.057	33.81	270.5	1,000	1

* In many photographic formulas the designation "cc" is used instead of "ml" to indicate the 1/1,000 part of a liter. Measures graduated in "ml" may be used for compounding processing formulas expressed in "cc."

SOLID CONVERSION VALUES

$$\left. \begin{array}{l} \text{Grains avdp} \\ \text{Ounces avdp} \\ \text{Pounds avdp} \end{array} \right\} \begin{array}{l} \text{per Brit. imp. quart (40 fl oz) multiplied} \\ \text{by 0.8327} \end{array} = \left\{ \begin{array}{l} \text{grains avdp} \\ \text{ounces avdp} \\ \text{pounds avdp} \end{array} \right\} \text{per U. S. quart (32 fl oz)}$$

$$\text{Grains avdp per Brit. imp. quart multiplied by 0.05702} = \text{grams per liter}$$

$$\text{Ounces avdp per Brit. imp. quart multiplied by 24.94} = \text{grams per liter}$$

$$\text{Pounds avdp per Brit. imp. quart multiplied by 399.1} = \text{grams per liter}$$

$$\text{Grams per liter multiplied by 17.54} = \text{grains avdp per Brit. imp. quart}$$

$$\text{Grams per liter multiplied by 0.04009} = \text{ounces avdp per Brit. imp. quart}$$

$$\text{Grams per liter multiplied by 0.002506} = \text{pounds avdp per Brit. imp. quart}$$

$$\text{Grains avdp per U. S. quart (32 fl oz) multiplied by 0.06847} = \text{grams per liter}$$

$$\text{Ounces avdp per U. S. quart (32 fl oz) multiplied by 29.96} = \text{grams per liter}$$

$$\text{Pounds avdp per U. S. quart (32 fl oz) multiplied by 479.3} = \text{grams per liter}$$

$$\text{Grams per liter multiplied by 14.60} = \text{grains avdp per U. S. quart (32 fl oz)}$$

$$\text{Grams per liter multiplied by 0.03338} = \text{ounces avdp per U. S. quart (32 fl oz)}$$

$$\text{Grams per liter multiplied by 0.002086} = \text{pounds avdp per U. S. quart (32 fl oz)}$$

LIQUID CONVERSION VALUES

$$\text{Ounces (fluid) per Brit. imp. quart multiplied by 0.8} = \text{ounces (fluid) per U. S. quart}$$

$$\text{Ounces (fluid) per Brit. imp. quart multiplied by 25.00} = \text{cubic centimeters per liter}$$

$$\text{Cubic centimeters per liter multiplied by 0.03999} = \text{ounces (fluid) per Brit. imp. quart}$$

$$\text{U. S. fluid ounces per U. S. quart (32 fl oz) multiplied by 31.25} = \text{milliliters per liter}$$

$$\text{Milliliters per liter multiplied by 0.032} = \text{U. S. fluid ounces per U. S. quart (32 fl oz)}$$

Appendix III

KODAK FORMULAS FOR PHOTOGRAPHIC PROCESSING SOLUTIONS

NEGATIVE DEVELOPERS

ELON (METOL)-HYDROQUINONE-BORAX DEVELOPER (Formula D-76)

A general-purpose developer for negatives, giving moderate contrast and maximum shadow detail.

	<i>Metric</i>	<i>Avoirdupois</i>	
		<i>British Imperial</i>	<i>United States</i>
Water (about 125° F) (52° C)	750.0 cc	120 oz	96 oz
Elon (or Metol)	2.0 grams	140 grains	116 grains
Sodium sulphite, crystals (or, anhydrous)	200.0 grams (100.0 grams)	32 oz (16 oz)	26 ½ oz (13 ¼ oz)
Hydroquinone	5.0 grams	350 grains	290 grains
Borax, granular	2.0 grams	140 grains	116 grains
Cold water to make	1.0 liter	160 oz	1 gallon

Dissolve the chemicals in the order given.

Use without dilution. Develop about 14 minutes in a tray or 17 minutes in a tank at 68° F (20° C). Greater or less contrast may be obtained by developing longer or shorter times than those indicated.

For tank development the use of the following replenisher is recommended. The life of the developer solution may be extended five to ten times by the use of this replenisher.

REPLENISHER FOR USE WITH FORMULA D-76 (Formula D-76R)

	<i>Metric</i>	<i>Avoirdupois</i>	
		<i>British Imperial</i>	<i>United States</i>
Water (about 125° F) (52° C)	750.0 cc	120 oz	96 oz
Elon (or Metol)	3.0 grams	210 grains	175 grains
Sodium sulphite, crystals (or, anhydrous)	200.0 grams (100.0 grams)	32 oz (16 oz)	26 ½ oz (13 ¼ oz)
Hydroquinone	7.5 grams	1 oz, 93 grains	1 oz
Borax, granular	20.0 grams	3 oz, 83 grains	2 oz, 290 grains
Cold water to make	1.0 liter	160 oz	1 gallon

Dissolve the chemicals in the order given.

Use the replenisher without dilution and add to the tank as required to maintain the level of the solution. Development times will require adjustment according to the extent of exhaustion of the solution.

ELON (METOL)-HYDROQUINONE DEVELOPER (Formula D-19)

A negative developer giving high contrast.

Stock Solution

	<i>Metric</i>	<i>Avoirdupois</i>	
		<i>British Imperial</i>	<i>United States</i>
Water (about 125° F) (52° C)	500.0 cc	80 oz	64 oz
Elon (or Metol)	2.2 grams	150 grains	128 grains
Sodium sulphite, crystals (or, anhydrous)	192.0 grams (96.0 grams)	30 ¾ oz (15 oz, 163 grains)	25 oz, 283 grains (12 oz, 360 grains)
Hydroquinone	8.8 grams	1 oz, 183 grains	1 oz, 75 grains
Sodium carbonate, crystals (or, anhydrous)	130.0 grams (48.0 grams)	20 ¾ oz (7 ¾ oz)	17 oz, 130 grains (6 oz, 180 grains)
Potassium bromide	5.0 grams	350 grains	290 grains
Cold water to make	1.0 liter	160 oz	1 gallon

Dissolve the chemicals in the order given.

Use without dilution for extreme contrast and develop about 7 minutes in a tray at 68° F (20° C). For less contrast, use one part stock solution to one part water, and develop about 5 minutes in a tray at 68° F (20° C). For still lower contrast, develop for shorter time, or use the developer more dilute, such as one part stock solution to four parts water.

ELON (METOL)-HYDROQUINONE-KODALK DEVELOPER (Formula DK-50)

For general use with films and plates.

Stock Solution

	<i>Metric</i>	<i>Avoirdupois</i>	
		<i>British Imperial</i>	<i>United States</i>
Water (about 125° F) (52° C)	500.0 cc	80 oz	64 oz
Elon (or Metol)	2.5 grams	180 grains	145 grains
Sodium sulphite, crystals (or, anhydrous)	60.0 grams (30.0 grams)	10 oz (5 oz)	8 oz (4 oz)
Hydroquinone	2.5 grams	180 grains	145 grains
Kodalk	10.0 grams	1 oz, 290 grains	1 oz, 145 grains
Potassium bromide	0.5 grams	35 grains	29 grains
Cold water to make	1.0 liter	160 oz	1 gallon

Dissolve the chemicals in the order given.

Use without dilution. Develop about 8 minutes in a tank at 68° F (20° C). For less contrast, take stock solution one part, water one part, and develop about 9 minutes in a tank at 68° F (20° C).

REPLENISHER SOLUTION FOR USE WITH DK-50
(Formula DK-50R)

	<i>Metric</i>	<i>Avoirdupois</i>	
		<i>British Imperial</i>	<i>United States</i>
Water (about 125° F) (52° C)	750.0 cc	120 oz	96 oz
Elon (or Metol)	5.0 grams	360 grains	290 grains
Sodium sulphite, crystals	60.0 grams	10 oz	8 oz
(or, anhydrous)	(30.0 grams)	(5 oz)	(4 oz)
Hydroquinone	10.0 grams	1 oz, 290 grains	1 oz, 145 grains
Kodalk	40.0 grams	6 oz, 245 grains	5 $\frac{1}{4}$ oz
Cold water to make	1.0 liter	160 oz	1 gallon

Dissolve the chemicals in the order given.

Add to the tank as needed to maintain the level of the solution. If the developer stock solution is diluted 1:1 for use, the replenisher should be diluted in the same proportion. The development time will require adjustment according to the extent of exhaustion of the solution.

RINSING AND FIXATION OF FILMS AND PLATES

After the development has been completed, the plates should be rinsed for at least 5 seconds in water and then placed in a clear acid-hardening fixing bath, such as F-10.

Freedom from stain formation will be assured, especially under hot weather conditions, by using the following hardening bath after the water rinse. The use of the chrome alum bath also extends the life of the fixing bath.

CHROME ALUM HARDENING BATH
(Formula SB-3)

	<i>Metric</i>	<i>Avoirdupois</i>	
		<i>British Imperial</i>	<i>United States</i>
Water	1.0 liter	160 oz	1 gallon
Potassium chrome alum	30.0 grams	5 oz	4 oz

When developed, rinse the films or plates for about 5 seconds in water, and place for 3 minutes in the hardening bath; then place immediately in the fixing bath.

Agitate the negatives for a few seconds when first immersed and at intervals while in the hardener SB-3; otherwise a chromium scum, which is very difficult to remove, may form on the surface of the negatives.

The chrome alum hardening bath should be renewed frequently, and, if any scum tends to form on the surface of the bath, it should be removed before the bath is used.

ACID-HARDENING FIXING BATH (Formula F-10)

For use with highly alkaline developers.

	<i>Metric</i>	<i>Avoirdupois</i>	
		<i>British Imperial</i>	<i>United States</i>
Water (about 125° F) (52° C)	500.0 cc	80 oz	64 oz
Sodium thiosulphate (hypo)	330.0 grams	3 lb, 7 oz	2 $\frac{3}{4}$ lb
Sodium sulphite, crystals	15.0 grams	2 $\frac{1}{2}$ oz	2 oz
(or, anhydrous)	(7.5 grams)	(1 $\frac{1}{4}$ oz)	(1 oz)
Kodalk	30.0 grams	5 oz	4 oz
Glacial acetic acid	19.5 cc	3 $\frac{1}{8}$ fl oz	2 $\frac{1}{2}$ fl oz
Potassium alum	22.5 grams	3 $\frac{3}{4}$ oz	3 oz
Cold water to make	1.0 liter	160 oz	1 gallon

Dissolve the chemicals in the order given.

Agitate films and plates when first placed in this bath and at intervals until fixation is completed.

Fix for twice the time to clear the material of its milky appearance. Wash thoroughly, and *wipe each negative carefully* before drying. When the time to clear has been increased, through use, to twice the time required with a fresh bath (about 20 minutes), the solution should be discarded. This will occur usually after about one hundred 8 x 10-in. films or plates (or their equivalent in other sizes) have been fixed per gallon (20 per liter).

PAPER DEVELOPER

ELON (METOL)-HYDROQUINONE DEVELOPER (Formula D-72)

A universal paper developer for contact prints and enlargements.

Stock Solution

	<i>Metric</i>	<i>Avoirdupois</i>	
		<i>British Imperial</i>	<i>United States</i>
Water (about 125° F) (52° C)	500.0 cc	80 oz	64 oz
Elon (or Metol)	3.1 grams	$\frac{1}{2}$ oz	180 grains
Sodium sulphite, crystals	90.0 grams	14 oz, 176 grains	12 oz
(or, anhydrous)	(45.0 grams)	(7 oz, 90 grains)	(6 oz)
Hydroquinone	12.0 grams	1 oz, 400 grains	1 oz, 260 grains
Sodium carbonate, crystals	180.0 grams	29 oz, 90 grains	24 $\frac{1}{2}$ oz
(or, anhydrous)	(67.5 grams)	(10 oz, 350 grains)	(9 oz)
Potassium bromide	1.9 grams	130 grains	$\frac{1}{4}$ oz
Cold water to make	1,000.0 cc	160 oz	1 gallon

Dissolve the chemicals in the order given.

For general use with contact and enlarging printing papers and lantern slides, take one part of the above solution to two parts of water.

Develop contact papers and Kodabromide about 60 seconds at 68° F (20° C). Develop bromide enlarging paper about 2 minutes at 68° F (20° C). Develop lantern slides 2 to 6 minutes at 68° F (20° C). For colder tones, dilute 1:1.

RINSING AND FIXING BATHS FOR PAPERS

ACETIC ACID RINSE BATH FOR PAPERS (Formula SB-1)

	<i>Metric</i>	<i>Avoirdupois</i>	
		<i>British Imperial</i>	<i>United States</i>
Water to	1.0 liter	160 oz	128 oz
Acetic acid (glacial)	13.5 cc	2 $\frac{1}{8}$ fl oz	1 fl oz, 5 $\frac{1}{2}$ drams

After development, rinse the prints for at least 5 seconds in the acid rinse before placing in the fixing bath. Use a fresh rinse bath for each batch of prints.

ACID-HARDENING FIXING BATH FOR PAPERS (Formula F-1)

	<i>Metric</i>	<i>Avoirdupois</i>	
		<i>British Imperial</i>	<i>United States</i>
Water	2.0 liters	80 oz	64 oz
Sodium thiosulphate (hypo)	480.0 grams	20 oz	16 oz

When thoroughly dissolved and cooled, add the entire volume of the following hardening solution:

Water (about 125° F) (52° C)	160.0 cc	6 $\frac{1}{4}$ oz	5 oz
Sodium sulphite, crystals	60.0 grams	2 oz, 180 grains	2 oz
(or, anhydrous)	(30.0 grams)	(1 oz, 90 grains)	(1 oz)
Glacial acetic acid	27.0 cc	1 fl oz	6 $\frac{3}{4}$ drams
Potassium alum	30.0 grams	1 oz, 90 grains	1 oz

Dissolve the hardener chemicals in the order given.

Dissolve the sulphite completely before adding the acetic acid. After the sulphite acid solution has been mixed thoroughly, add the potassium alum, with constant stirring. Cool hardener solution, and add slowly to cool hypo solution, stirring rapidly.

Immerse the prints, face up, with occasional agitation, for 10 to 15 minutes in the fixing bath.

Wash thoroughly for at least 1 hour in running water which flows fast enough to replace the water in the tray 10 to 12 times per hour.

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